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PROTOTYPE LOW TEMPERATURE LOW POWER CRYOCOOLER,(U)
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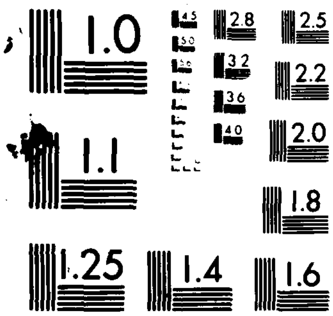


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

Prototype Low Temperature Low Power Cryocooler

by

Warren G. Pierce

February 1982

Prepared under Contract No. N00014-80-C-0825

by

LAKE SHORE CRYOTRONICS, INC.
Westerville, Ohio 43081

for

OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY

PROTOTYPE LOW TEMPERATURE LOW POWER CRYOCOOLER

INTRODUCTION

Over the past several years considerable interest has developed for low power, low cost mechanical cryocoolers for use in cooling SQUIDS and other superconducting devices.

In 1977 Dr. Jim Zimmerman of National Bureau of Standards, Boulder, CO described a stirling cycle cryocooler(1) that exhibited the following desirable characteristics:

(1) Low input power (approximately 50 watts connected load);

(2) Modest cooling capacity at very low temperature;

(3) Constructed of non-ferromagnetic materials;

(4) Simple design.

Dr. Zimmerman's intent was to demonstrate the feasibility of constructing a simple low power cryocooler capable of cooling an operational SQUID. After several modifications of the original cryocooler, Dr. Zimmerman successfully operated a point-Contact Nb SQUID on a four-stage stirling cycle cryocooler with a mechanical drive power of approximately 15 watts, and a capacity of few milliwatts at less than 9 Kelvin.(2)

Dr. Zimmerman's goal was realized and considerable interest developed within CTi-Cryogenics, Fort Belvoir, S.H.E., Lake Shore Cryotronics, Inc. and others.

During this period Lake Shore Cryotronics, Inc. successfully negotiated an exclusive licensing (for the U.S.) agreement with Oxford Instruments

Ltd. concerning a simple patented[3] single stage cryocooler utilizing a slide-valve-controlled gas driven displacer drive head, powered by a remote conventional high speed compressor. Since this Cryocooler does not require any electric motors or signals to be present in the coldhead, it appeared that when constructed of non-magnetic materials and mated with a cylinder/displacer assembly of Zimmerman's design, a simple reliable coldhead might result.

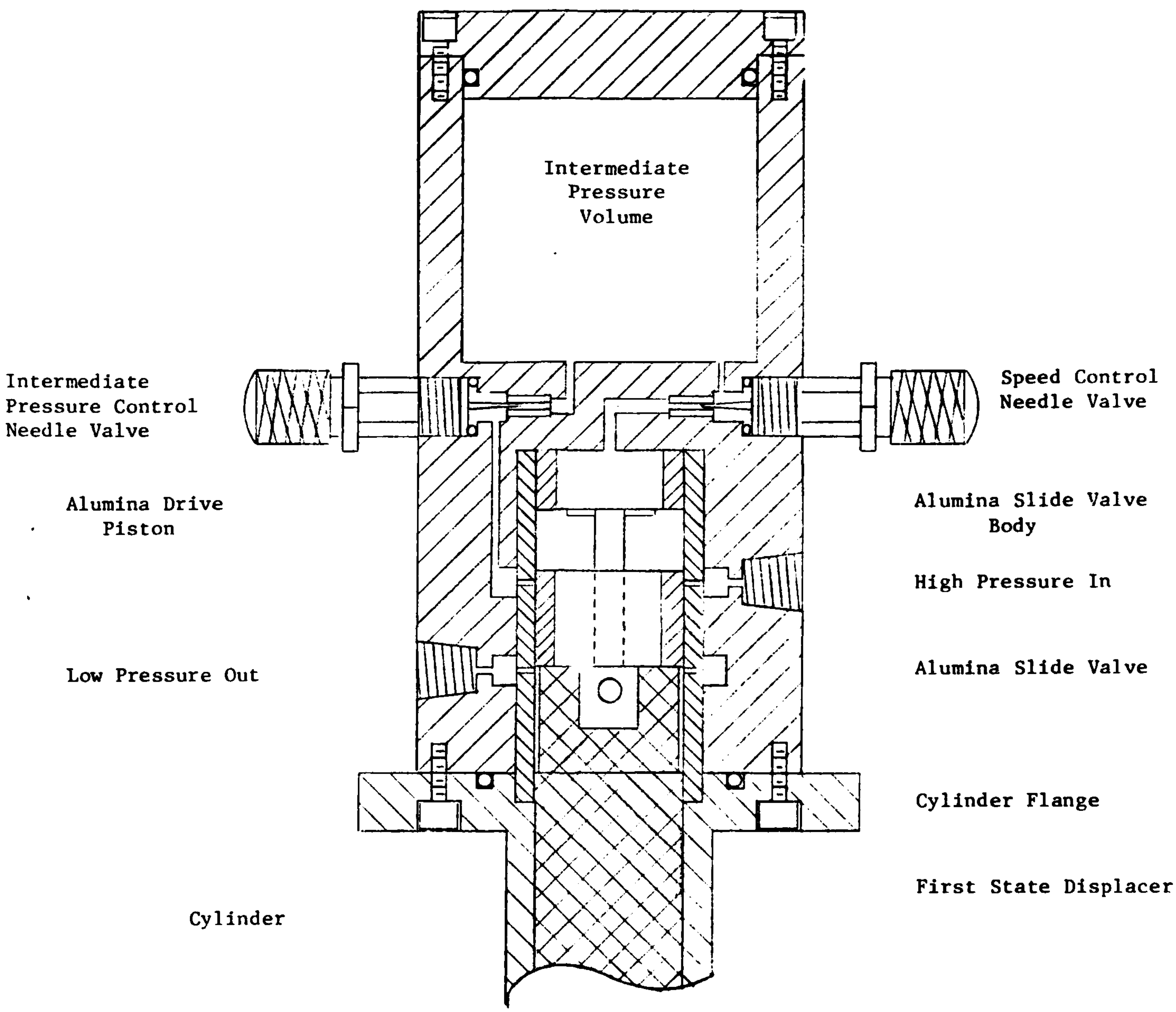
No major problems were expected in building a prototype coldhead as both portions of it (cylinder/displacer assembly and drive head) had been proven in different devices.

PROTOTYPE CONSTRUCTION

The prototype coldhead was constructed as shown in Figures 1 and 2 (2 stage cylinder/displacer). The cylinder/displacer assemblies were designed after that of Zimmerman, though we took particular care to ensure a close fit between the cylinder and displacer. Each stage of the cylinder was bored and then honed to high tolerances of both concentricity and diameter along its length. The two and four stage displacers were machined from Nylon(R) stock as two (and four) separate pieces and joined with epoxy using socket joints and epoxy-filled opposing grooves to lock each stage together. The two-stage cold finger was built because of problems encountered with earlier four stage u[illegible] The main difficulty was in joint integrity and the simpler cold fing[illegible] made adjustment of the radial clearance easier. The displacer fit smoothly into the cylinder such that the only resistance to motion was due to the compression/suction pressure in the expansion space.

The drive unit body was machined from aluminum with all manifolds and interconnecting gas ports machined into the body. The speed control needle valve and intermediate pressure control needle valve were made from standard commercially available needle valve stems attached to the drive unit body by o-ring sealed adapters. The valve seats were

ONR CRYOCOOLER DRIVE UNIT



Scale:

1 cm

Figure: 1

ONR CRYOCOOLER CYLINDER

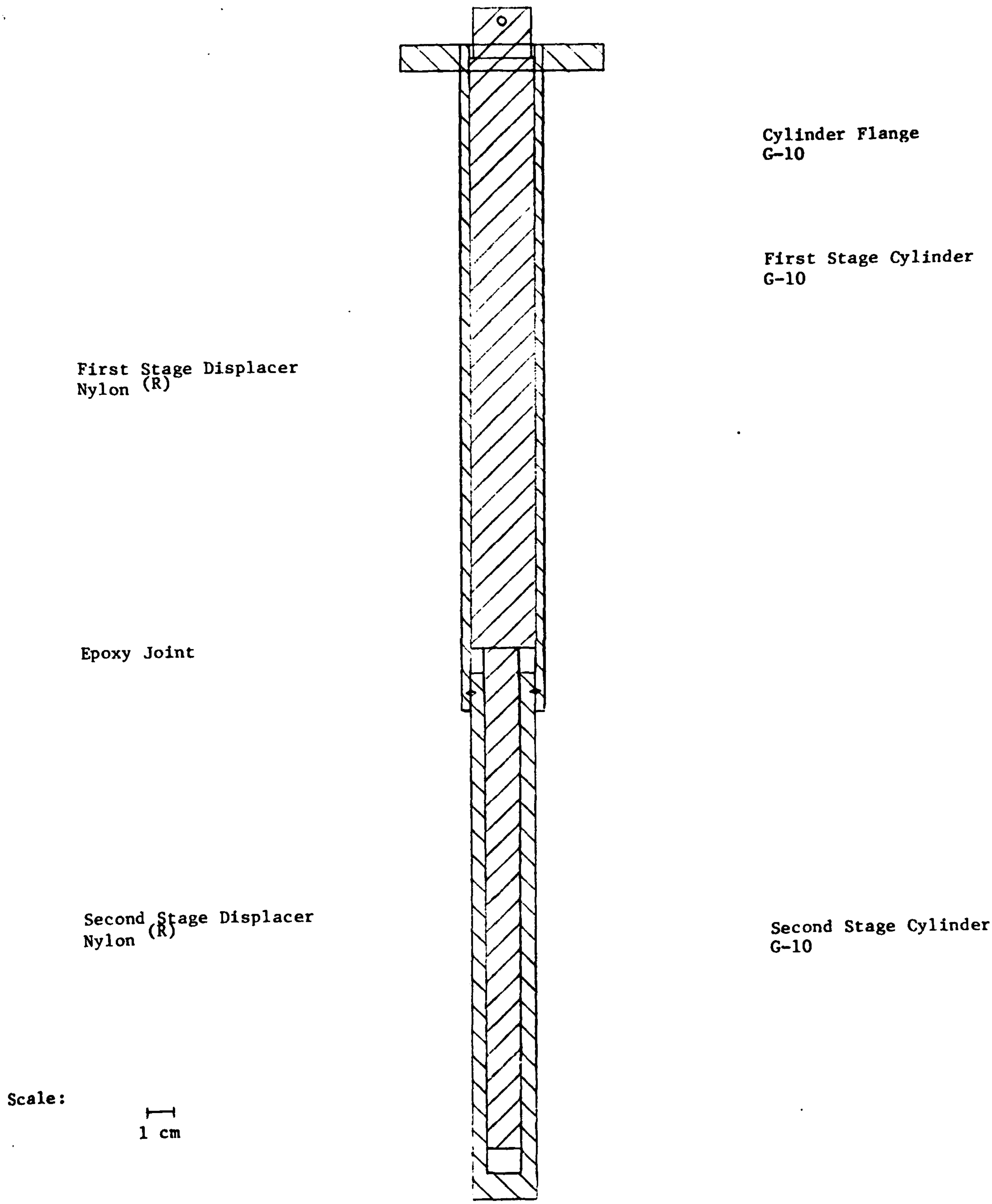


Figure: 2

machined directly into the coldhead body. The slide valve, drive pistons, and slide valve body were made from high density alumina. The slide valve and piston were centerless ground to fit the slide valve body (honed bore) with less than .0025mm radial clearance. This produced a nearly frictionless fit of all parts. A groove was cut in the surface of the slide valve to allow installation of a fluorocarbon drag ring to prevent the slide valve from "floating" within the valve body. The connecting rod was machined from Nylon(R) and the drive piston was epoxied to the drive rod which was in turn attached to the displacer by a single G-10 pin. The high and low pressure valve ports consist of two sets of holes drilled radially through the ceramic valve body.

A CTi-Cryogenics Model 21SC helium compressor was used to run the coldhead after initial testing on helium from a standard high pressure cylinder. A special manifold was constructed to allow adjustment of the pressure difference between the supply and suction sides of the compressor.

RESULTS

In the first few attempted cooldown tests of the coldhead, the machine cycled very rapidly at approximately 6-8Hz. The machine stopped cycling at 220 to 270 kelvin. After stopping, the second stage continued to cool indicating that either the upper stage had actually cooled to lower temperatures or a large thermal gradient developed across the walls of the G-10 cylinder. Since the annular clearance between the displacer and cylinder was quite small ($\approx$.013mm), it was suspected that very little gas was transferring to and from the expansion spaces.due to high speed.

By gradually reducing the diameter of the displacers to increase the radial gap subsequent cooldowns produced lower temperatures, but the

machine ran at even higher cycle rates (8-10Hz).

In all runs the machine slowed from its initial high cycle rate to a lower cycle rate as it cooled. In addition, if the cycle rate was allowed to drop below 3-5Hz, the cryocooler usually stalled.

Much effort was put into improving the needle valve ports to allow better control of both intermediate pressure and speed. While these improvements helped, it was only after modifying the displacer that low cycle rates were attained. The modified displacer was tapered so that the radial gap was larger at the top than at the bottom of each stage. This allowed better helium flow in the cold finger during cooldown and produced a more uniform radial gap along the displacer length once it had cooled.

With these changes we were able to operate the cryocooler at less than 2Hz though the displacer motion was not harmonic due to unexplained imbalanced forces. The lowest temperature achieved at this point was 25k.

Due to the unbalanced motion problems and to generate P-V information, we attached a motion transducer to the displacer/drive piston assembly and installed a pressure transducer in the volume above the displacer.

When the cryocooler was adjusted for uniform motion of the displacer in both directions (requiring a high cycle rate) a P-V diagram as depicted in Figure 3 was derived.

In order to help slow the speed and change the motion of the displacer, a stroke control, as depicted in Figure 5, was designed and incorporated into the drive unit. The addition of the stroke control piston allowed the machine to be run at considerably lower cycle rates (down to $\leq$2Hz) while at the same time improved the shape of the P-V diagram (see Figure 4).

ONR CRYOCOOLER P-V DIAGRAM

(without stroke control)

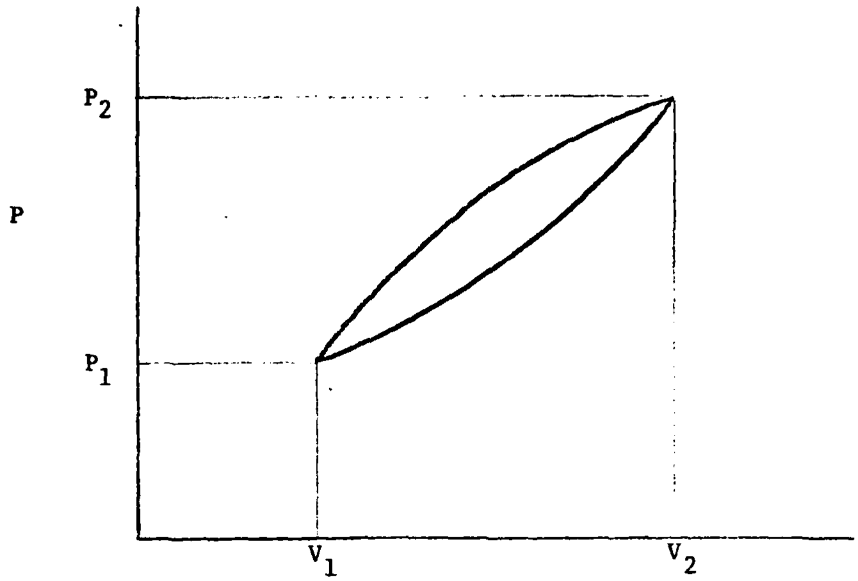


Figure: 3

ONR CRYOCOOLER P-V DIAGRAM

(with stroke control)

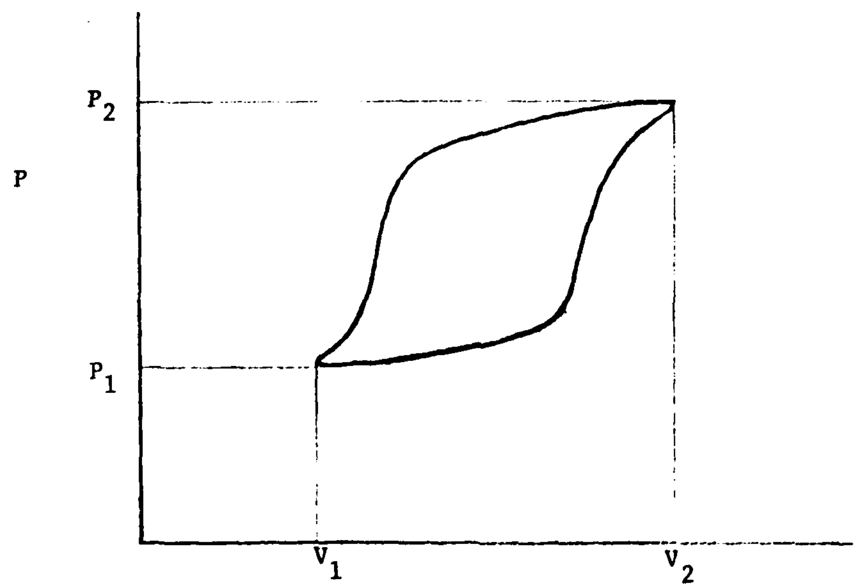


Figure: 4

The stroke control piston acted as a motion damper by forcing the drive piston to compress gas on either side of it during each half of a cycle. This effectively slowed the displacer during the middle 50% of its movement, while, by venting the compressed gas during the last 25% of the stroke, the displacer was allowed to move freely and produce positive valve action.

Though we were able to achieve low cycle rates after adding the stroke control, adjustment was tedious and operation at cycle rates below 3Hz was not always reliable.

We believe this was due primarily to gas leakage around the slide valve which limited the adjustment range of the speed control needle valve.

With the addition of the stroke control, the cycle rate was generally lower and performance was better, though there were exceptions.

The cooldown shown in Plot No. 3 (Appendix A) shows very good performance (lowest temperature of 25K). In this particular run the Cryocooler operated at relatively low speed without the stroke control. It must be noted that in this particular run the Cryocooler ran smoothly with an even stroke in both directions.

When one compares the data from runs with and without the stroke control, improvement in performance due to the stroke control becomes evident in light of the fact that the majority of runs with the stroke control were made with a two-stage cylinder/displacer.

The most serious continuing problem encountered was leakage at the epoxy joints between stages of the G-10 cylinder. We believe the reasons that leaks continued to plague the project was due to high stresses at the epoxy joints caused by large temperature differences across the joints. These were aggravated by the rapid cooling of the machine.

Another minor problem was encountered throughout the program. This was the inability of the Cryocooler to reliably self-start when the compressor is first started. This is due to the slide valve getting "trapped" in the center of the slide valve body with leakage between the high and low pressure ports. This situation occurs when either the slide valve comes to rest in this position when the Cryocooler is stopped or on start-up if insufficient momentum in the displacers initial motion to fully close one part during the first half cycle.

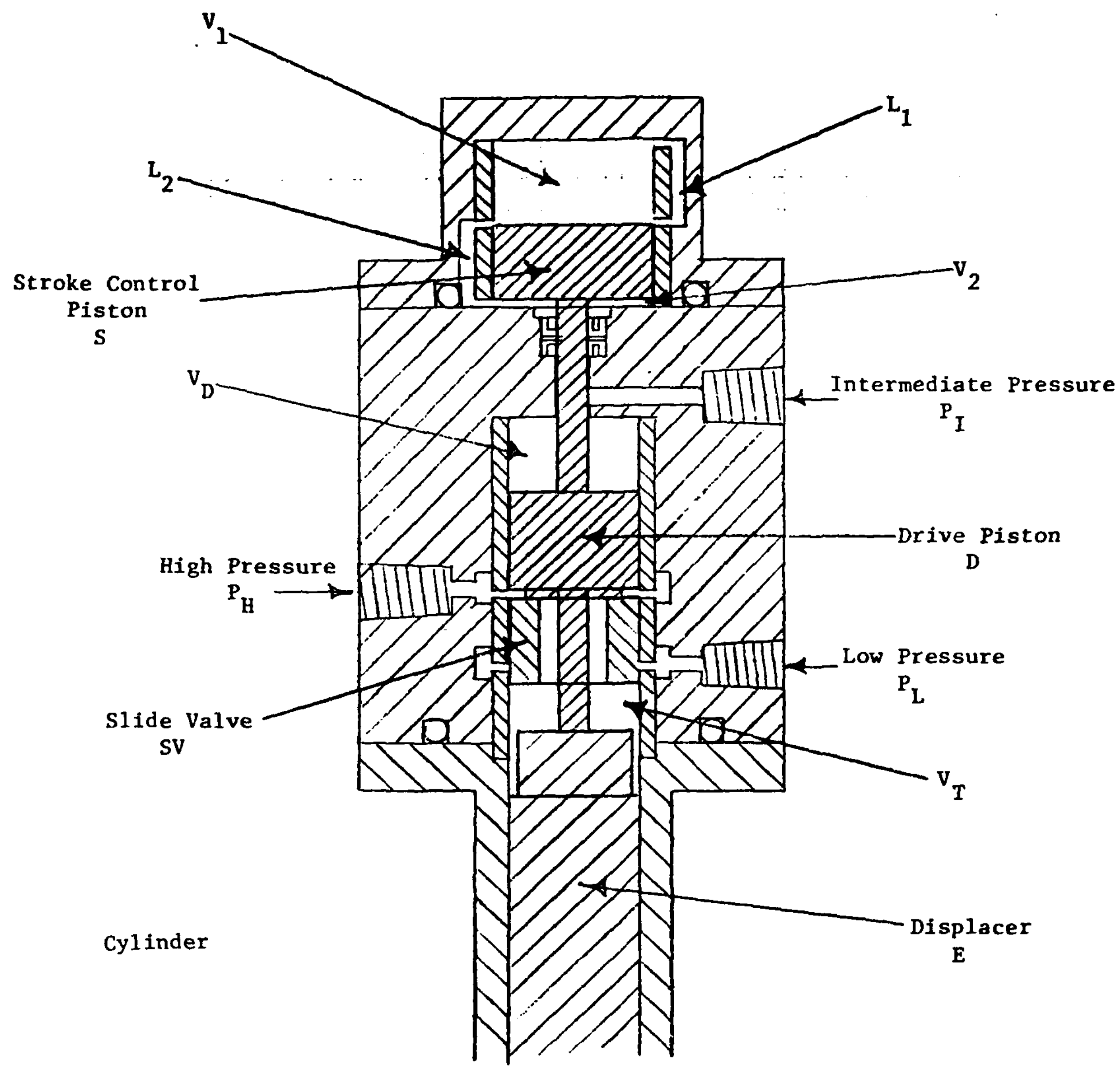
During our experiments we routinely opened, momentarily, the intermediate pressure volume to either the high or low pressure supply, thus causing the displacer to move completely to either extreme of its stroke.

STROKE CONTROL

Figures 5 through 9 depict the operation of the Cryocooler with the stroke control added.

In an ideal Cryocooler the displacer would remain stationary at both the top and bottom of its stroke for a period of time just long enough to allow a complete pressure change in the Cryocooler cylinder (plus expanion volume and regenerator). Since this is not easily accomplished in a practical Cryocooler, the best alternative is to slow the displacer during pressure changes.

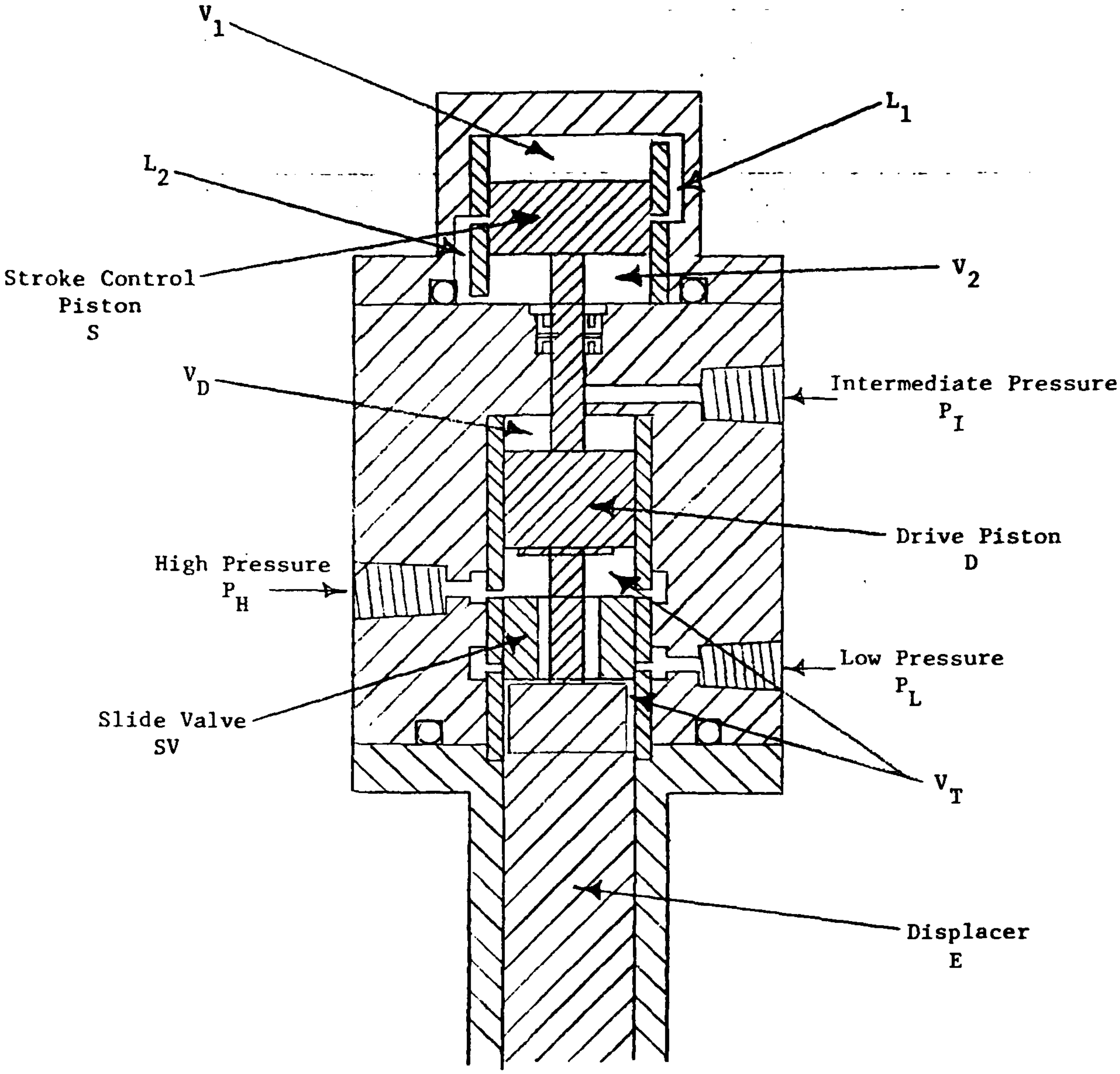
In the ONR Cryocooler incorporating the Loeb drive, the displacer is driven by the pressure difference (across the drive piston) between the intermediate volume and the volume below the drive piston (includes cylinder volume, expansion space and all void volumes). One can easily visualize that the displacer will begin, and continue, to move long before a complete pressure change takes place in the cylinder unless some means is provided to impede the displacer motion.



(1) The slide valve has just been moved to close the exhaust valve (P_L) and open the inlet valve (P_H).

(2) Gas flows into volume V_T and as the pressure in V_T becomes greater than the intermediate pressure P_I (in volume V_D), the displacer begins to move upward.

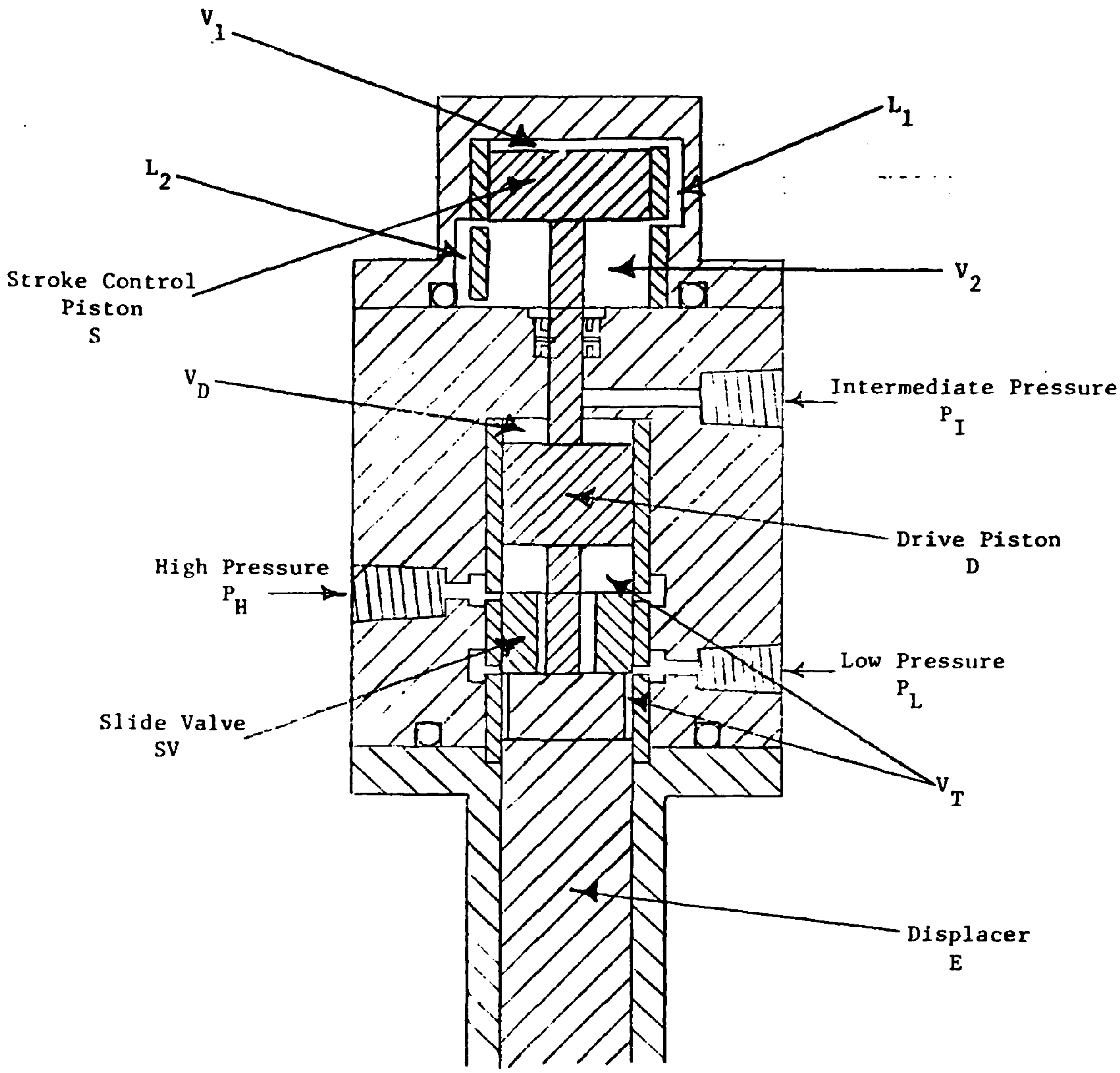
Figure: 5



(3) As the displacer moves up it is slowed due to the added force produced as the stroke control piston S compresses gas in volume V_1.

(4) This action allows the pressure in V_T and the cylinder to approach P_H before the displacer completes its upward stroke.

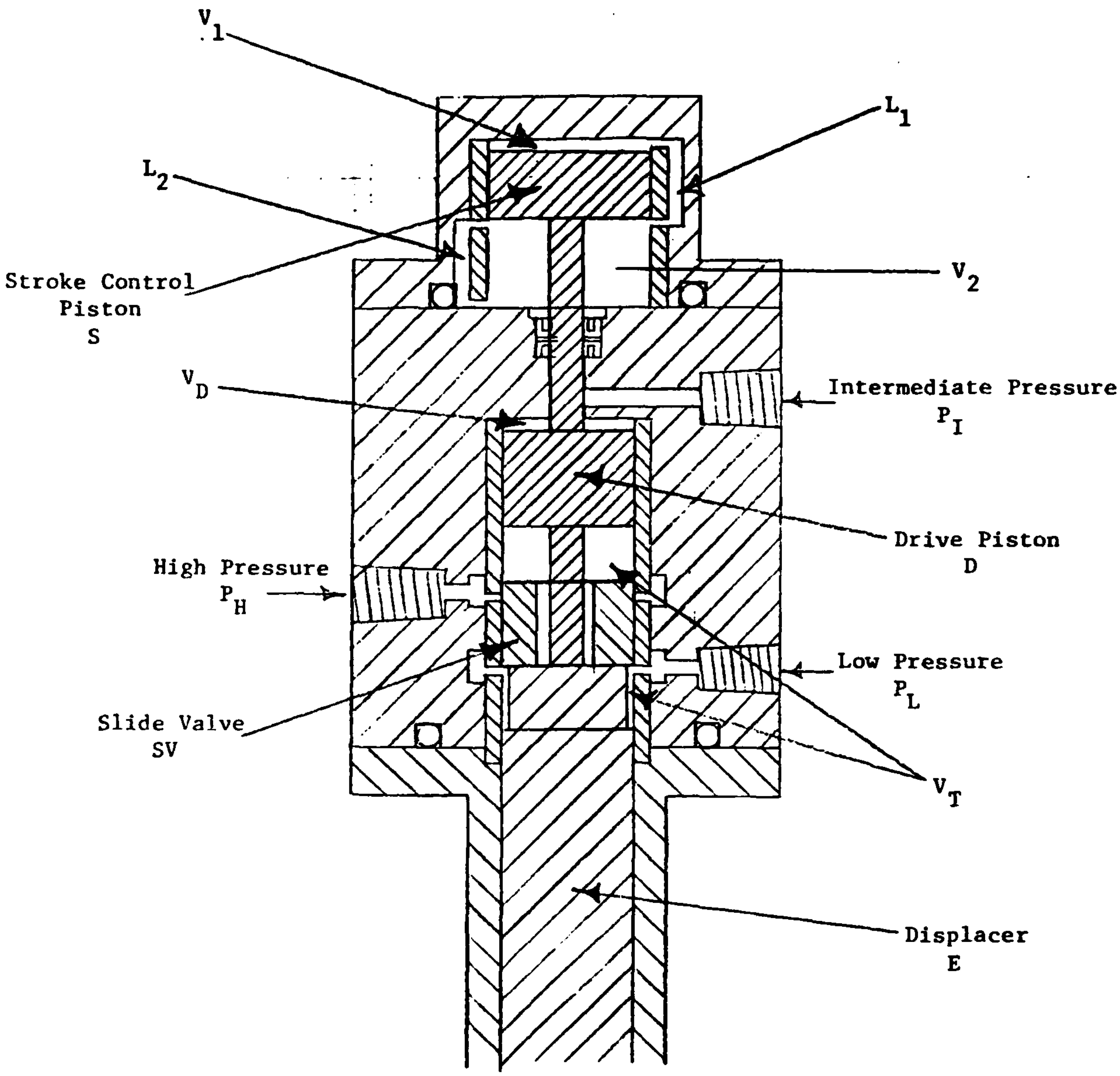
Figure: 6



(5) As the displacer reaches the position shown, the pressure in V_1 is equalized with the pressure in V_2 through L_1 allowing the displacer to move freely to the end of its upward stroke.

(6) In this last free motion the slide valve SV is moved closing the high pressure port and opening the low pressure port (see next figure).

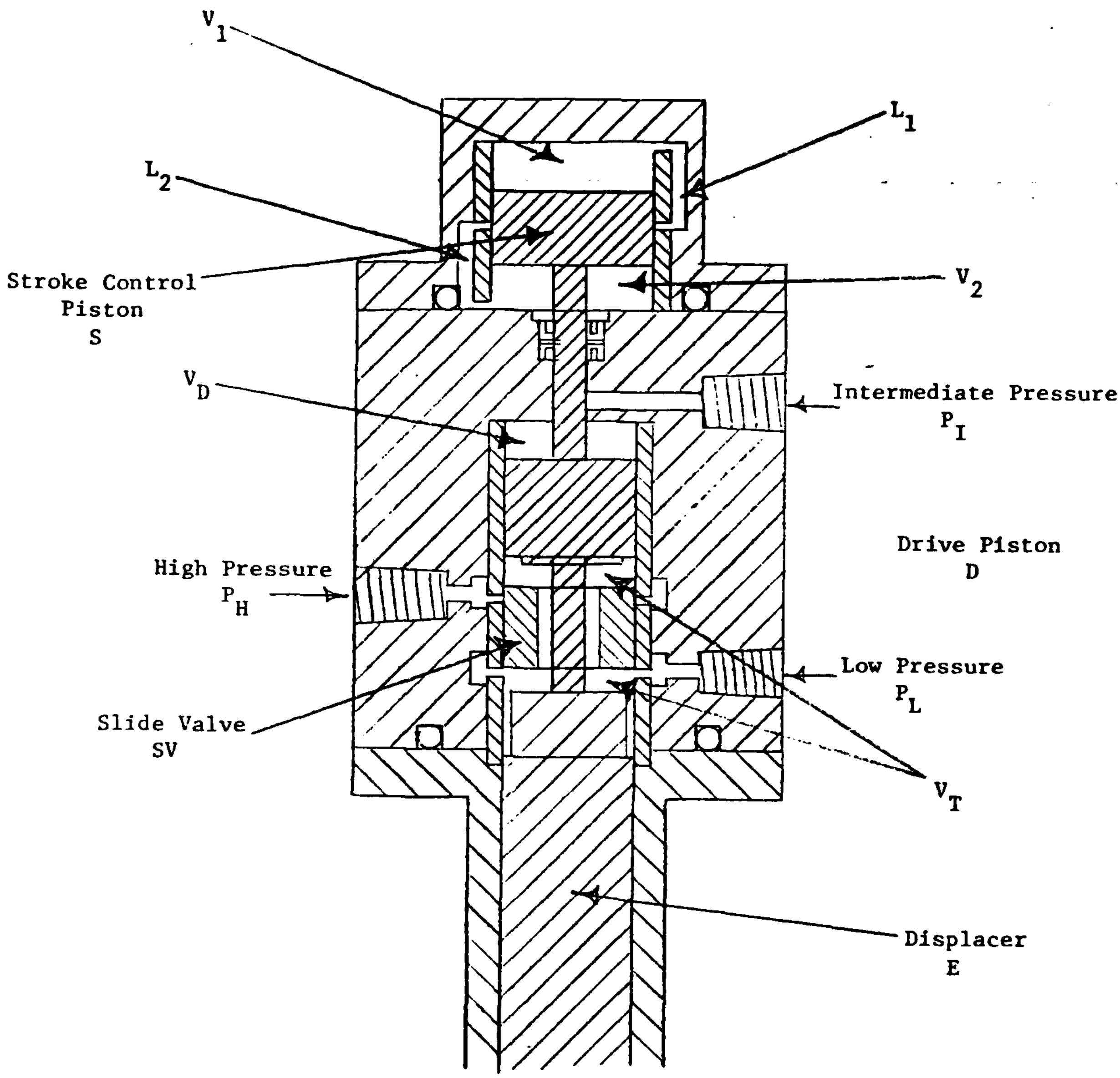
Figure: 7



(7) The exhaust port is now open and the pressure in V_T (and the cylinder) starts to drop.

(8) As the pressure in V_T drops below P_I, the displacer begins to move downward.

Figure: 8



(9) As the displacer moves down, it is slowed due to the added force produced as the stroke control piston S compresses gas in volume V_2.

(10) This action allows the pressure in V_T and the cylinder to approach P_L before the displacer completes its downward stroke.

(11) As the displacer approaches the position shown in Figure 5, the pressure in V_2 is equalized with the pressure in V_1 through line L_2 and the displacer completes its downward stroke while moving the slide valve to close the exhaust port and open the inlet port. The cycle then repeats.

Figure: 9

The stroke control accomplishes this by causing the force produced by the pressure difference across the drive piston to work against the additional force placed on the stroke control piston as gas is compressed in the stroke control volumes.

The stroke control described is applicable to any gas driven Cryocooler regardless of the valving mechanism employed. There are many existing Cryocooler designs which could benefit from this device.

In order to function properly, the stroke control volumes and piston area must be determined based on design parameters of the particular Cryocooler.

DATA

The Appendix contains 19 plots of cooldown test made on the Cryocooler during performance of the contract.

All temperature measurements were made with a Lake Shore Cryotronics, Inc. Model DRC-70 Digital Cryogenic Temperature Indicator and Model DT-500CU-DRC-36 Silicon Diode Cryogenic Temperature Sensor.

CONCLUSION

At this point all of the funds available under the contract had been expended, so work ceased awaiting continued funding.

The lowest temperature achieved was less than 20 kelvin with the two-stage cylinder/displacer operating at a cycle rate of 2Hz, 100 psi inlet (pressure), and 20 psi outlet pressure.

Had we been able to continue work on the machine, we are confident even lower temperatures would have been achieved with the two-stage cylinder displacer. With four stages as originally designed, the goal of 50 milliwatts of cooling capacity at 8.5 kelvin and a no-load temperature of 8 kelvin would almost certainly have been achieved.

To achieve this goal, it would be necessary to do the following:

First, redesign the slide valve to lengthen the leakage paths between the high and low pressure ports.

Second, once good performance is demonstrated with a two-stage displaced, three and four-stage displacers should be built to optimize the Cryocooler for the lowest operating temperature and cooling capacity.

Third, a control circuit should be added to allow momentarily opening the intermediate pressure volume to either the high or low pressure line to reliably start the Cryocooler.

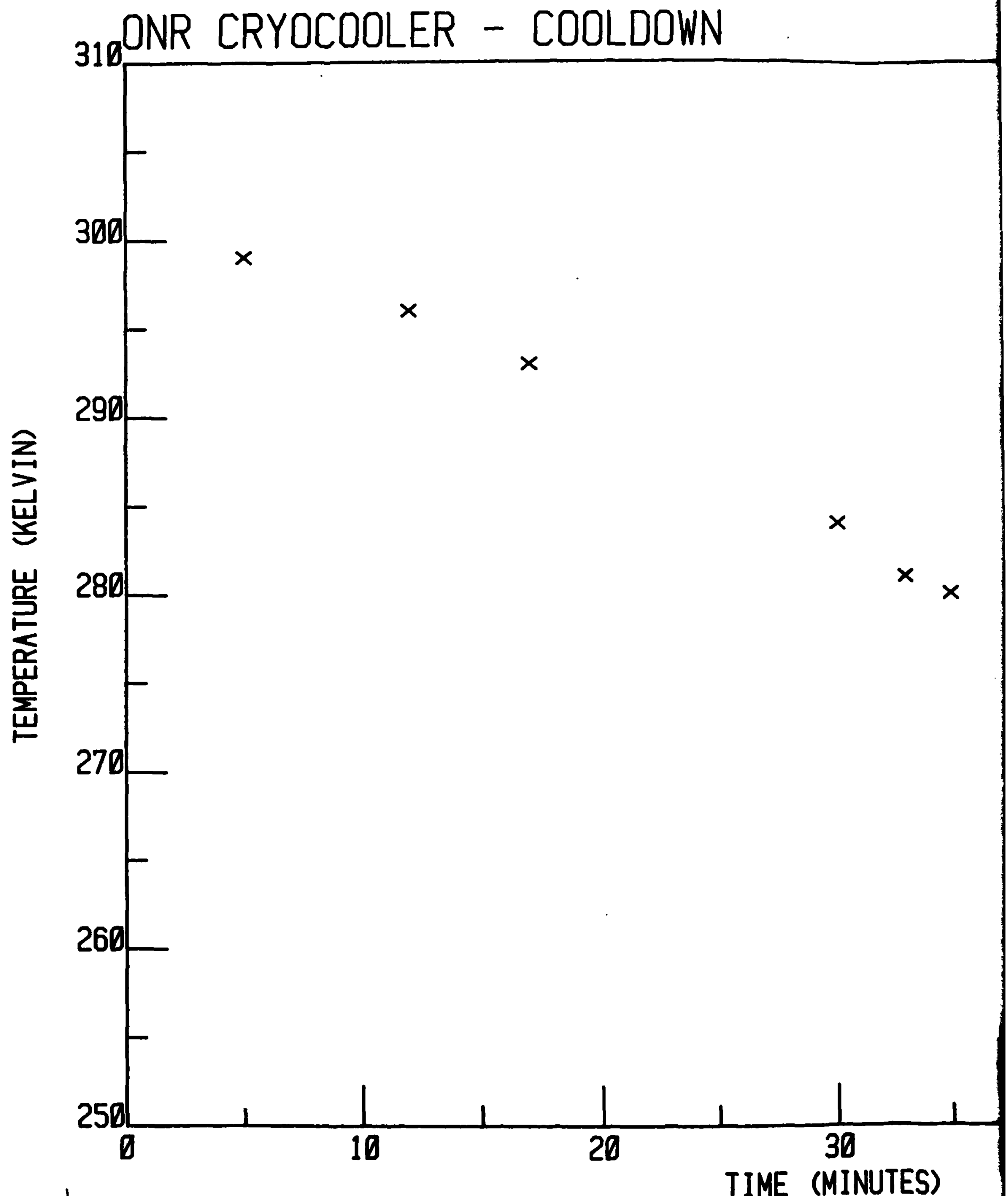
REFERENCES

(1) J.E. Zimmerman, R. Radebaugh and J.D. Siegworth, "Possible Cryocoolers for SQUID Magnetometers," Superconducting Quantum Interference Devices and Their Applications. H.D. Hahlbohm and H. Lubbig, eos., Walter de Gruyter, Berlin (1977) p 287.

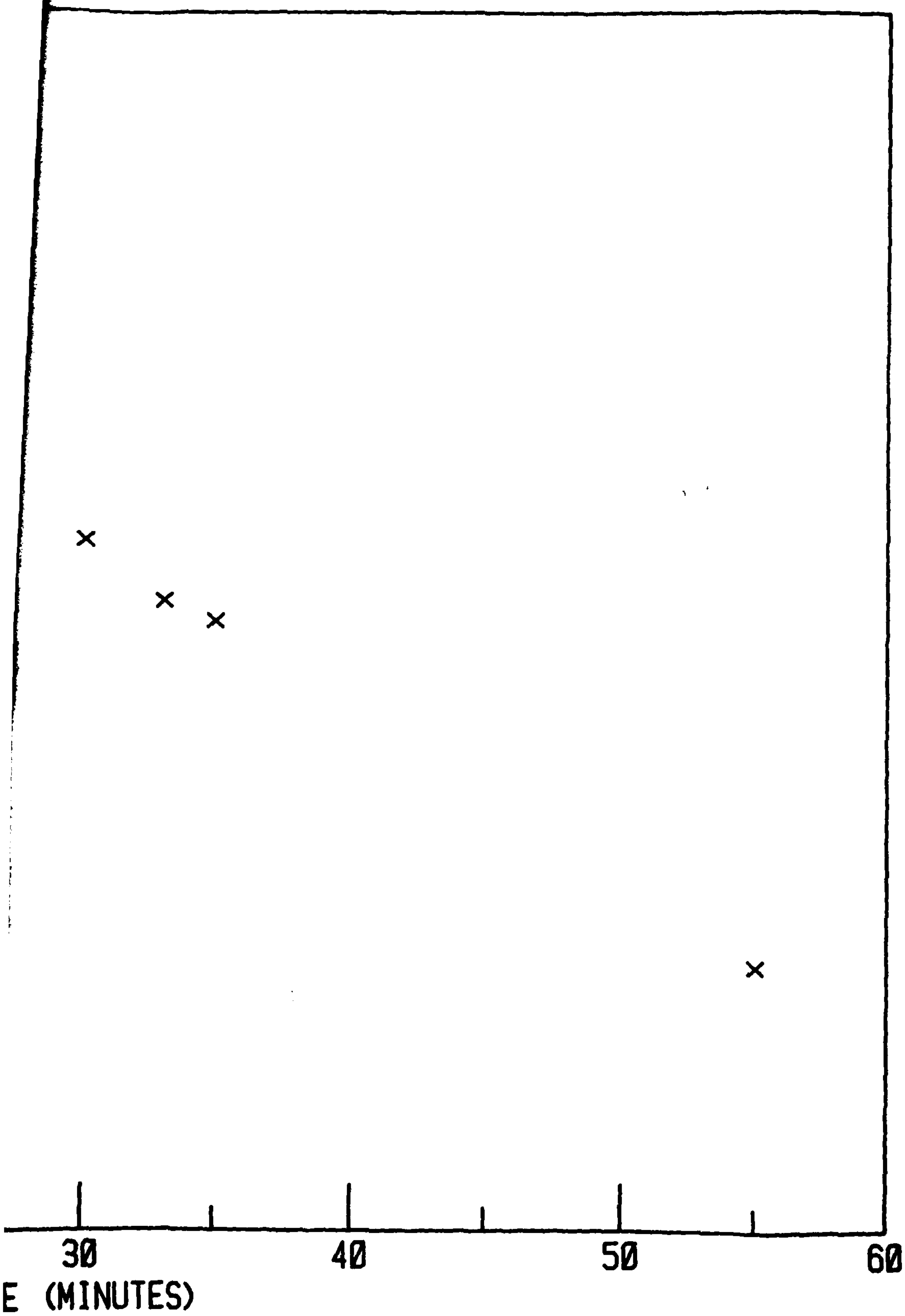
(2) J.E. Zimmerman and R. Radebaugh, "Operation of a SQUID in a Very Low-Power Cryocooler," NBS Special Publication 508 (1978).

(3) United States Patent Number 3,733,837.

APPENDIX



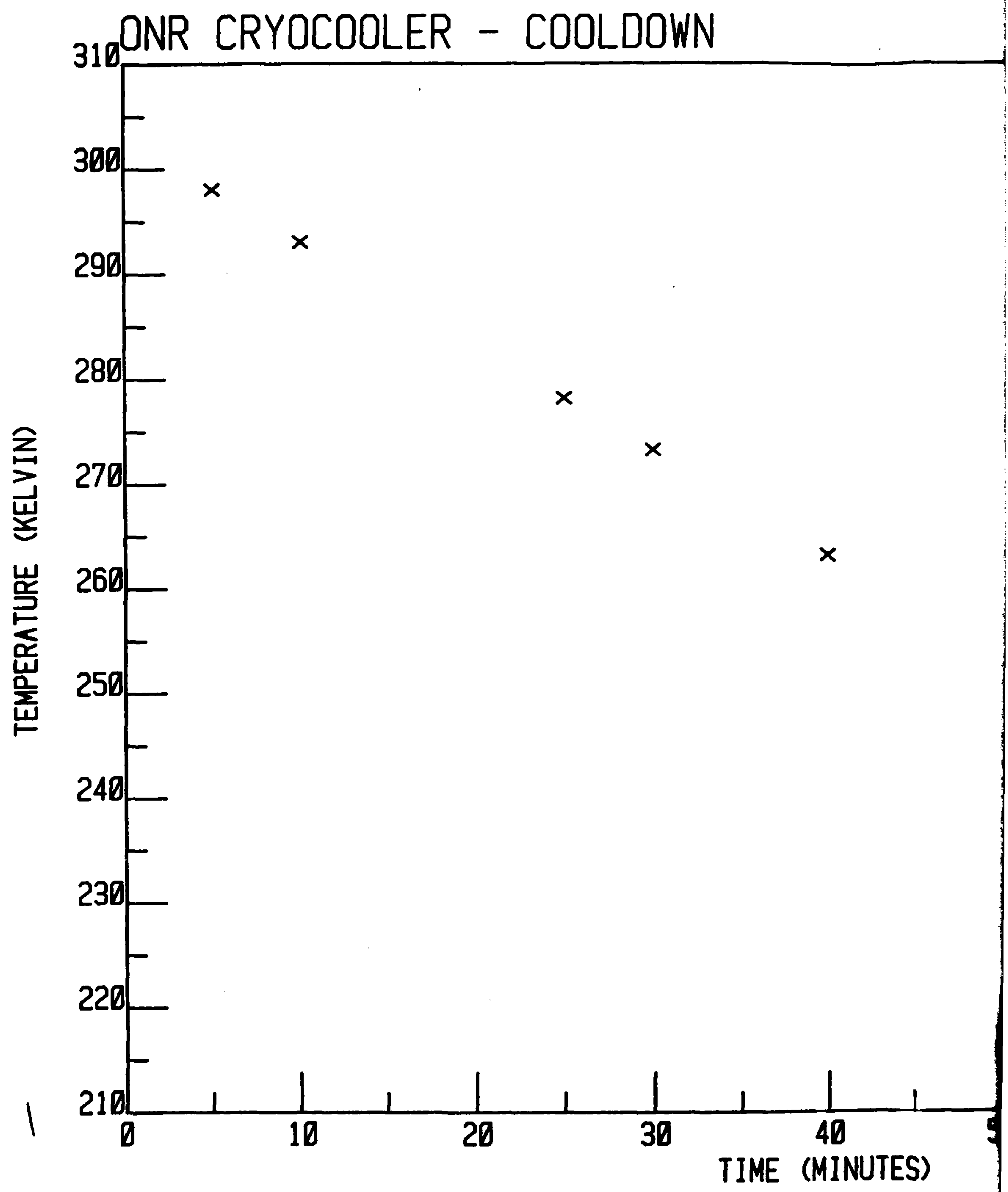
ONR CRYOCOOLER - COOLDOWN
310
300
290
280
270
260
250
TEMPERATURE (KELVIN)
0
10
20
30
TIME (MINUTES)

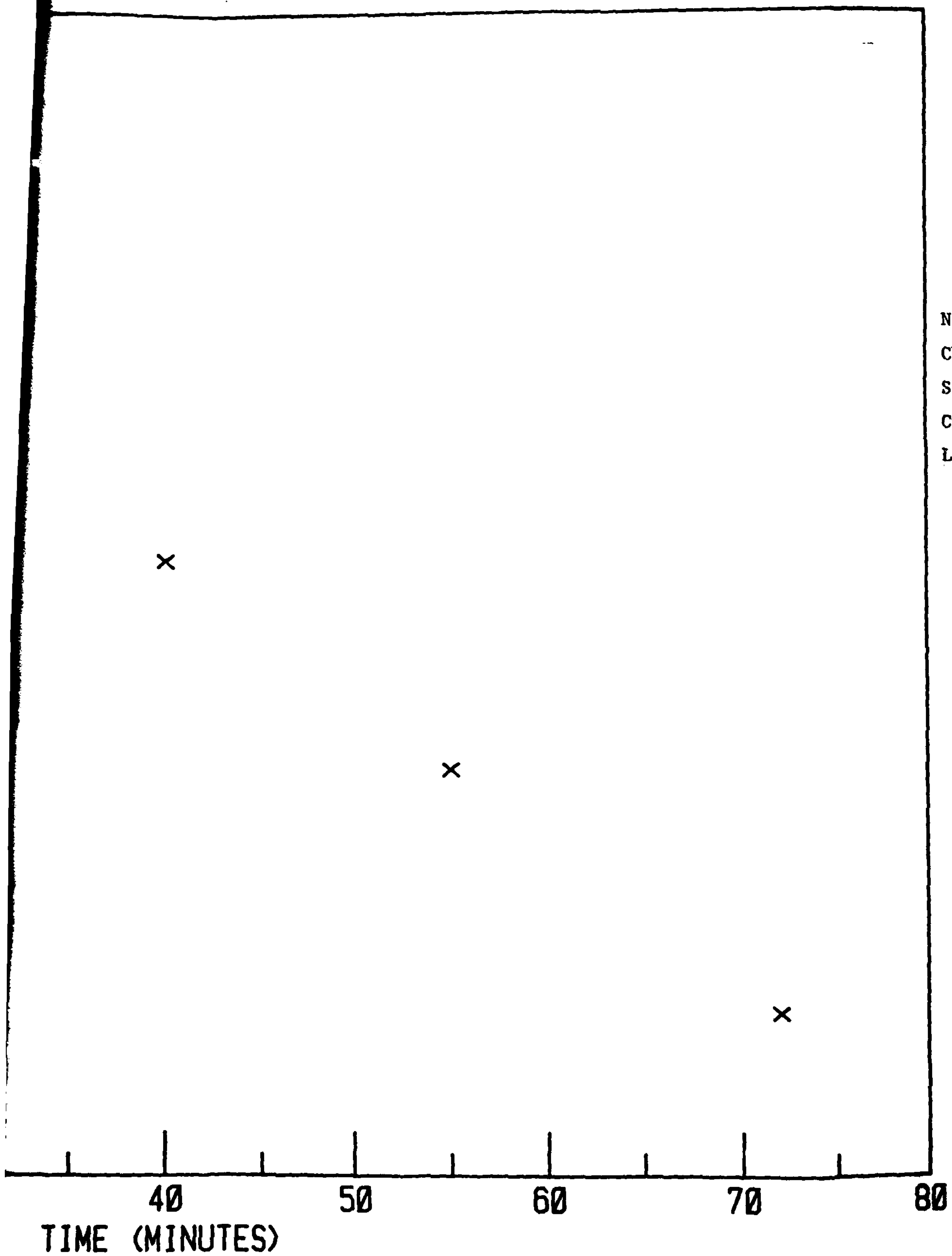


PLOT NO. 1

No. of Stages:	4
Charge Pressure:	.6MPa
Stroke Control:	None
Cycle Rate:	5-6Hz
Lowest Temperature:	263k

2

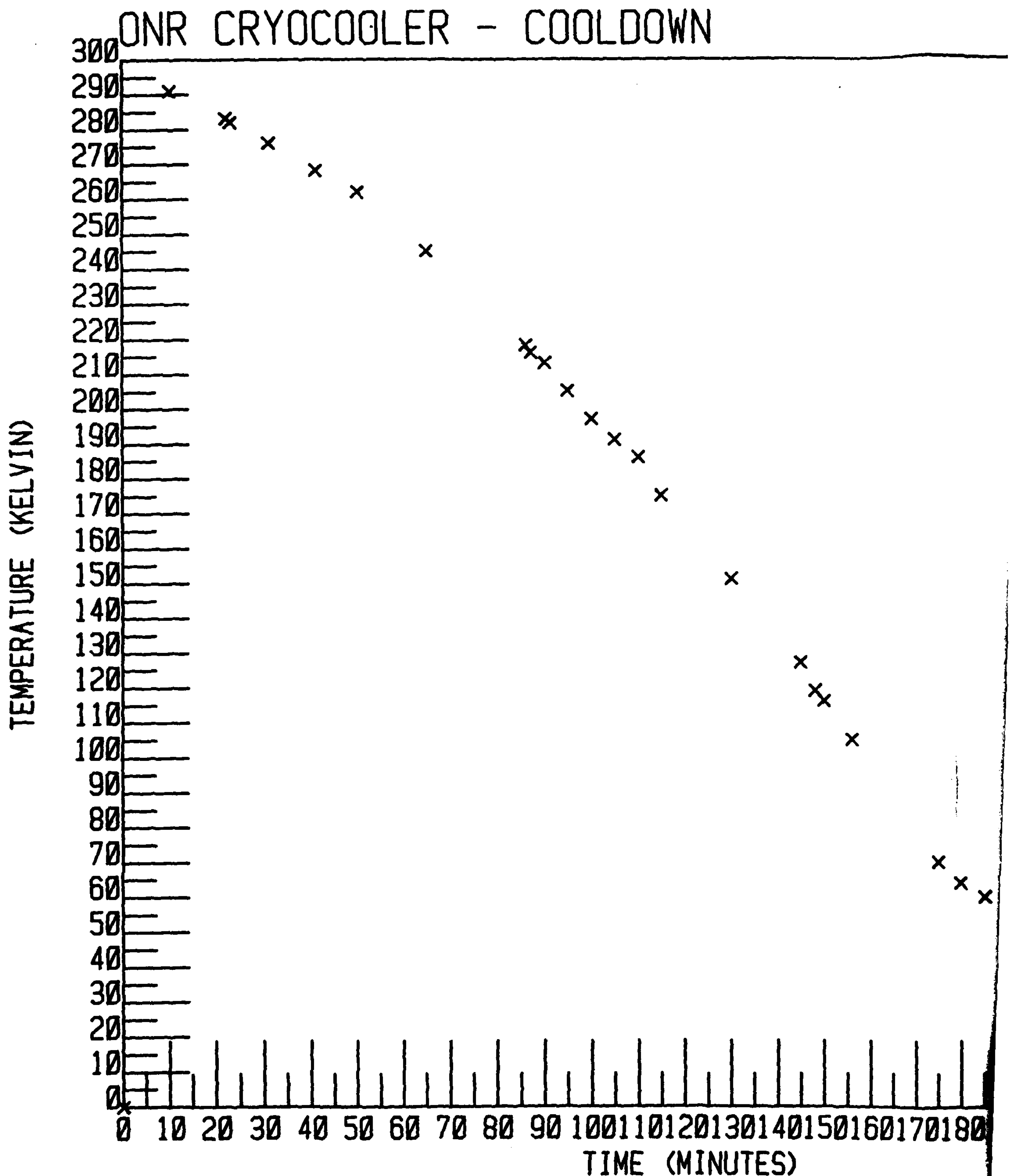

ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
310
300
290
280
270
260
250
240
230
220
210
0
10
20
30
40
TIME (MINUTES)

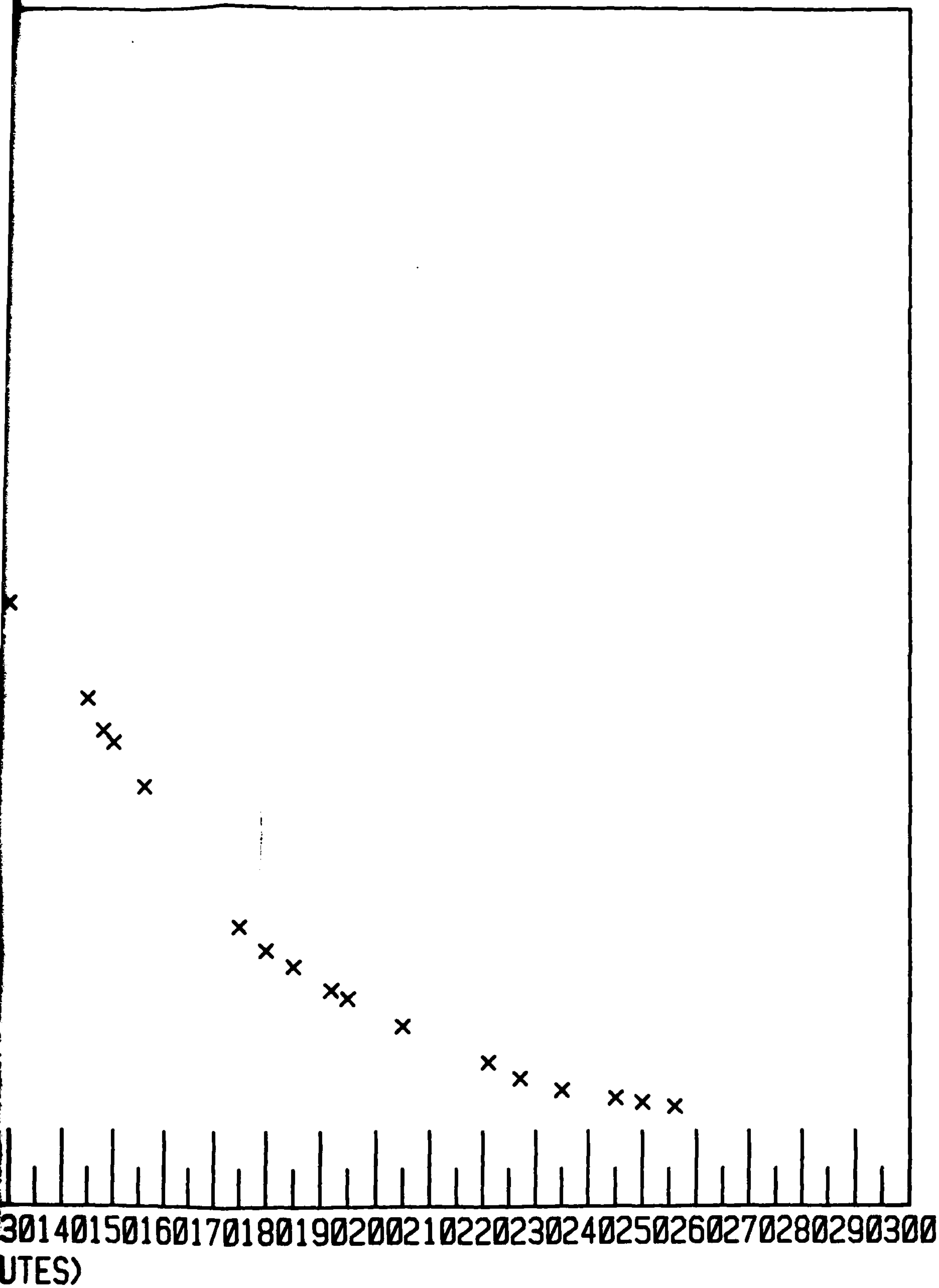


PLOT NO. 2

No. of Stages:	4
Charge Pressure:	.6MPa
Stroke Control:	None
Cycle Rate:	.5Hz
Lowest Temperature:	224k

2

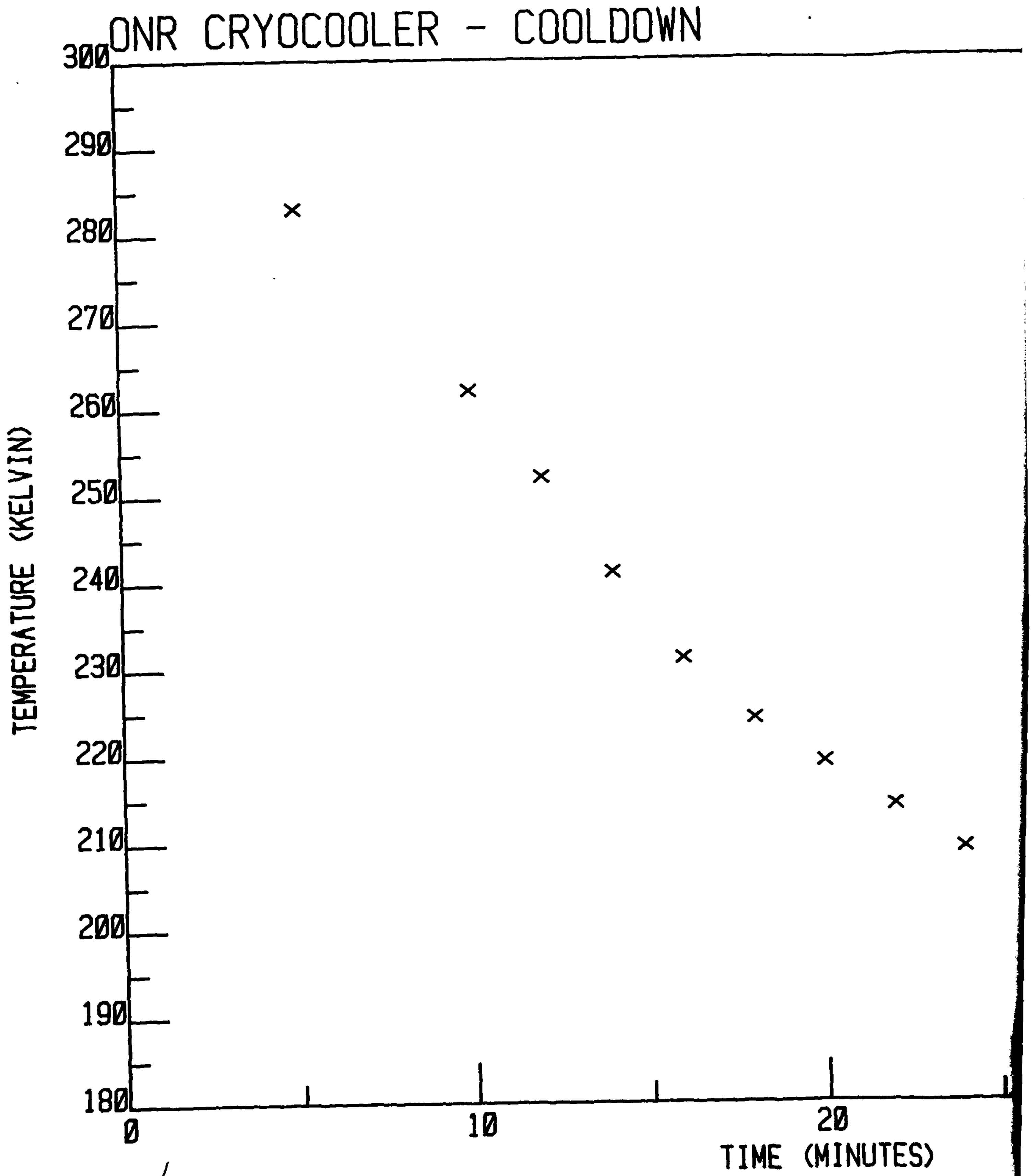

ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
TIME (MINUTES)
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180



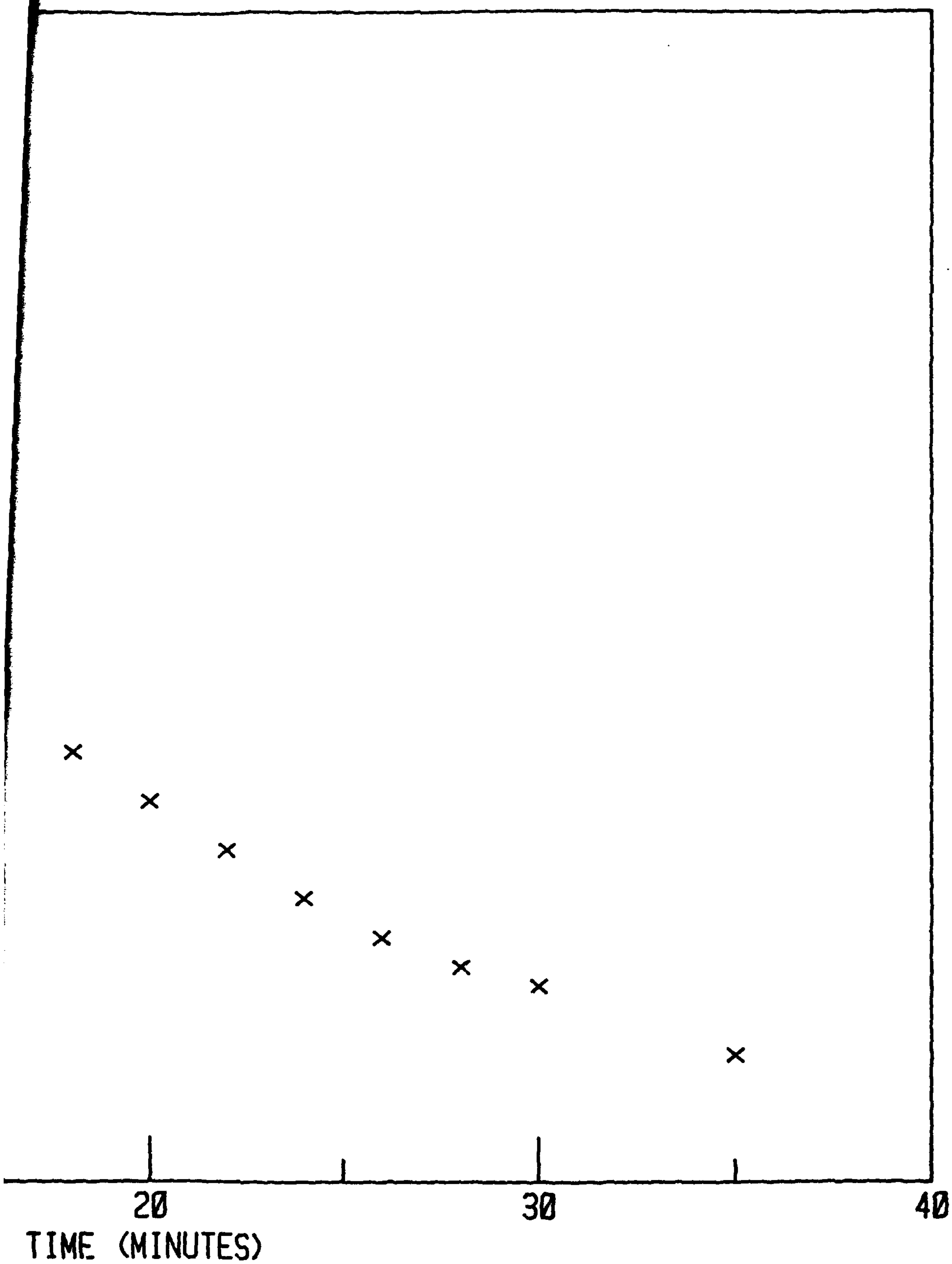
PLOT NO. 3

No. of Stages:	4
Charge Pressure:	.45MPa
Stroke Control:	None
Cycle Rate:	3.5-6H
Lowest Temperature:	25K

2



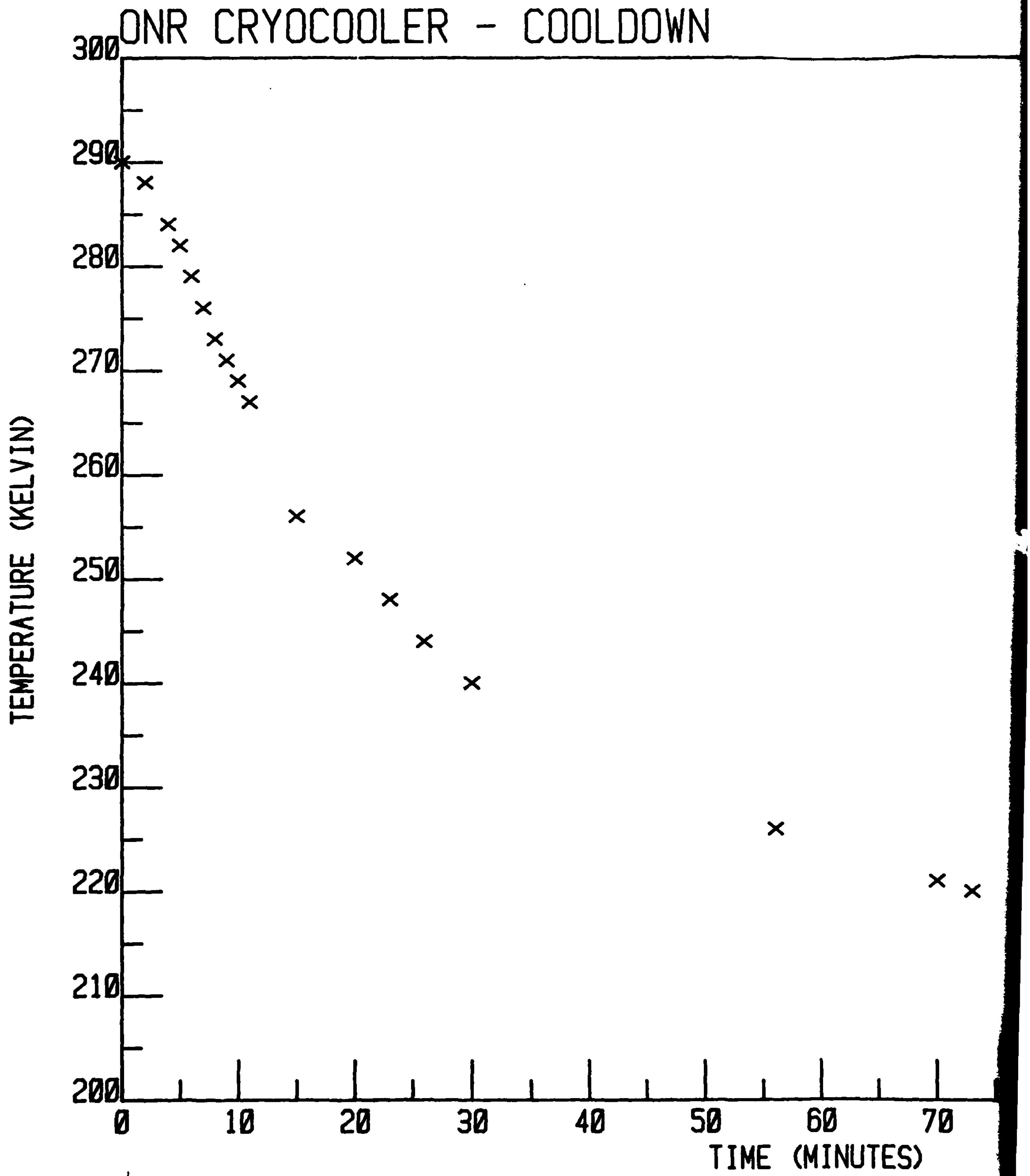
ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
210
200
190
180
0
10
20
TIME (MINUTES)



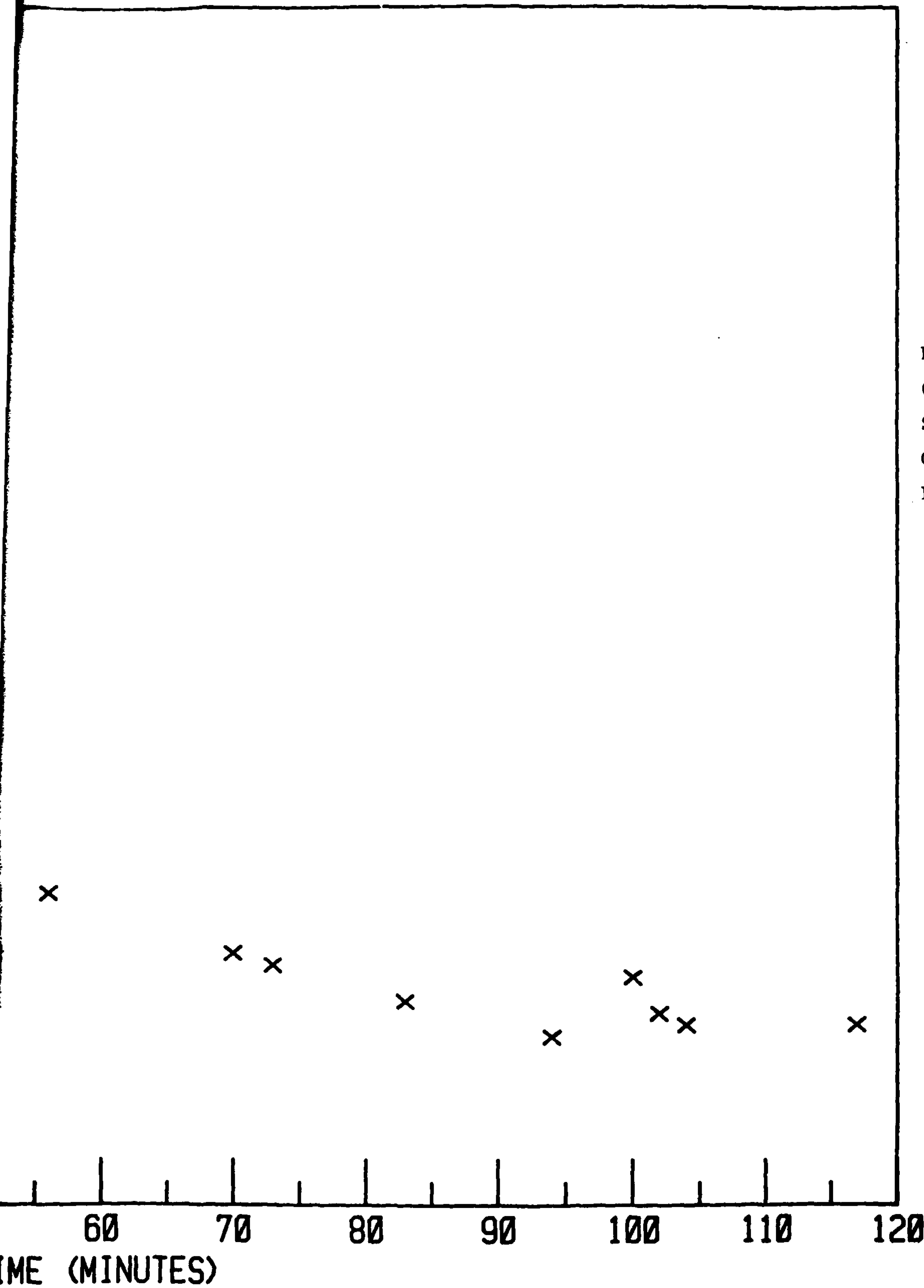
PLOT NO. 4

No. of Stages:	2
Charge Pressure:	1MPa
Stroke Control:	None
Cycle Rate:	6-10
Lowest Temperature:	193k

2



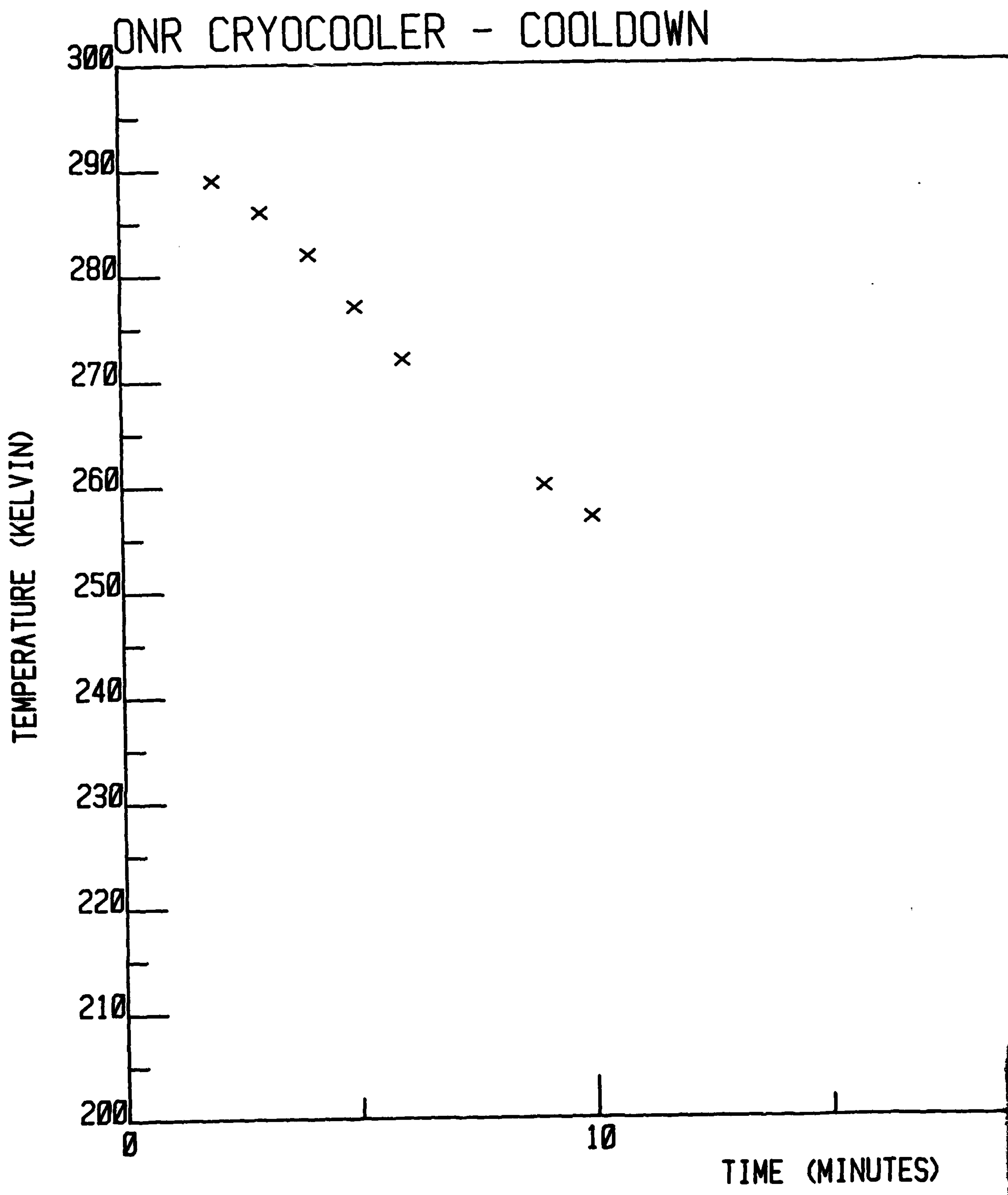
ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
210
200
0
10
20
30
40
50
60
70
TIME (MINUTES)



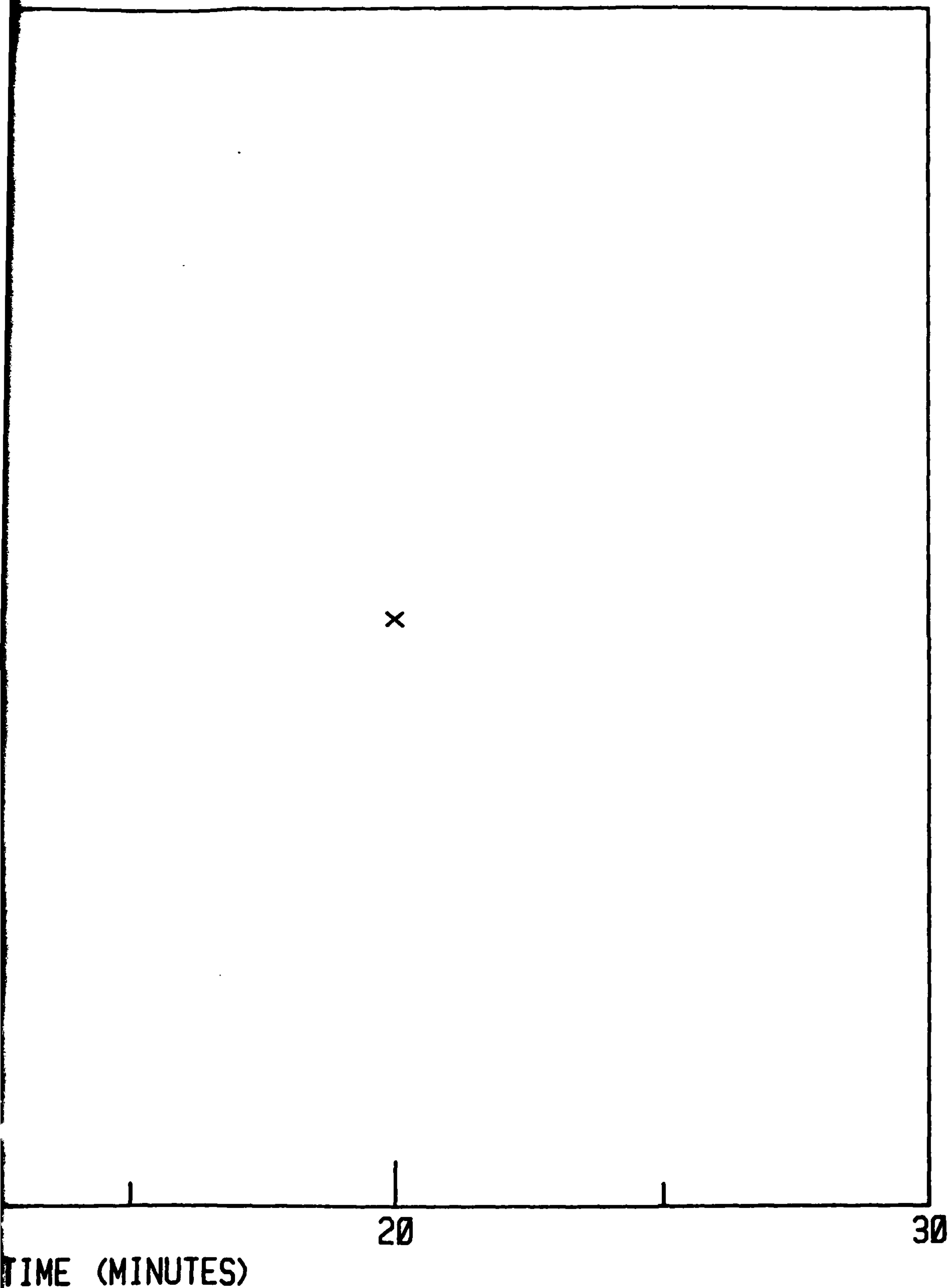
PLOT NO. 5

No. of Stages:	2
Change Pressure:	.6MPa
Stroke Control:	None
Cycle Rate:	1.5-3Hz
Lowest Temperature:	215K

2



ONR CRYOCOOLER - COOLDOWN
300
290
280
270
260
250
240
230
220
210
200
TEMPERATURE (KELVIN)
0
10
TIME (MINUTES)



PLOT NO. 6

No. of Stages: 2

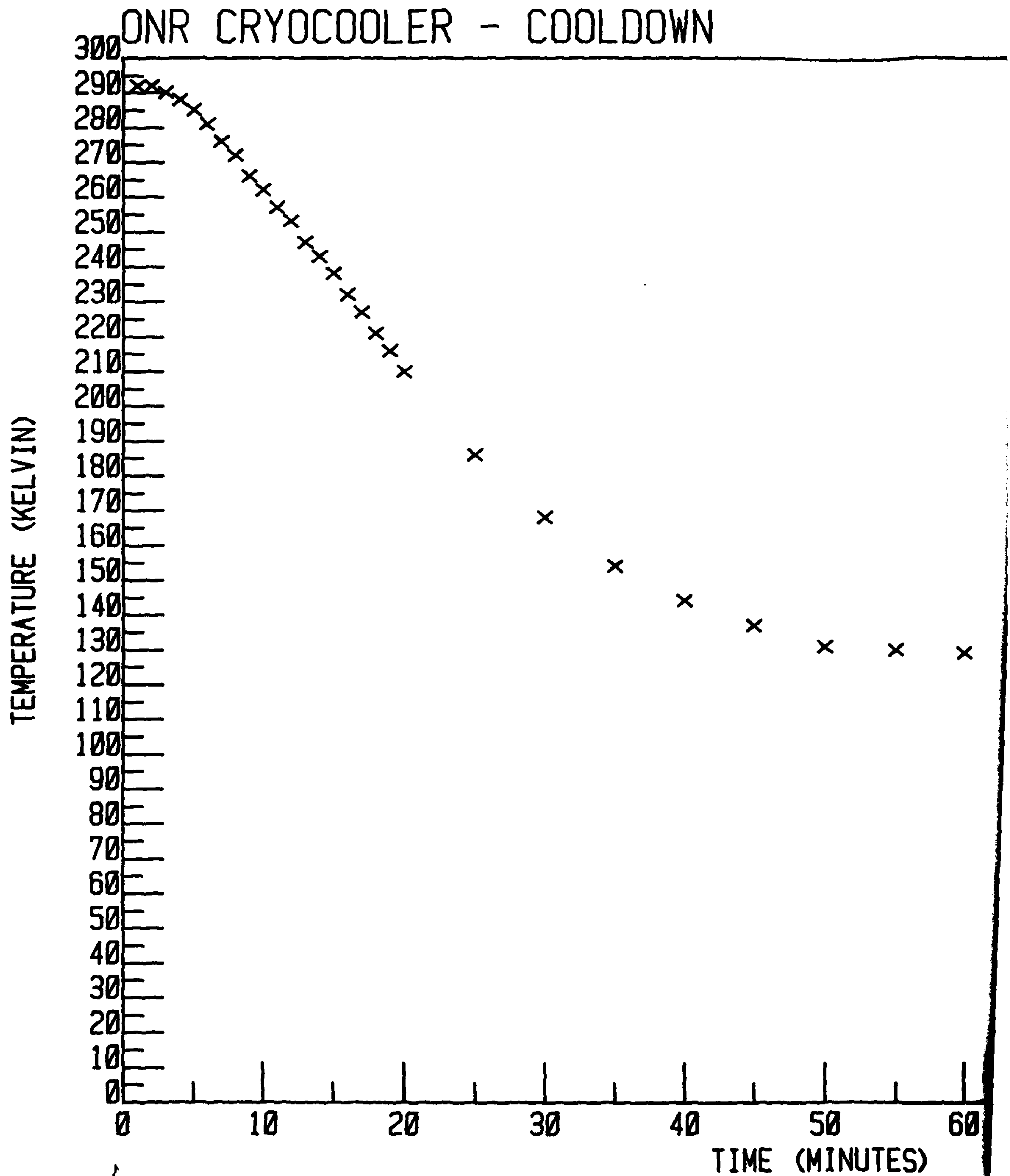
Charge Pressure: .6MPa

Stroke Control: yes

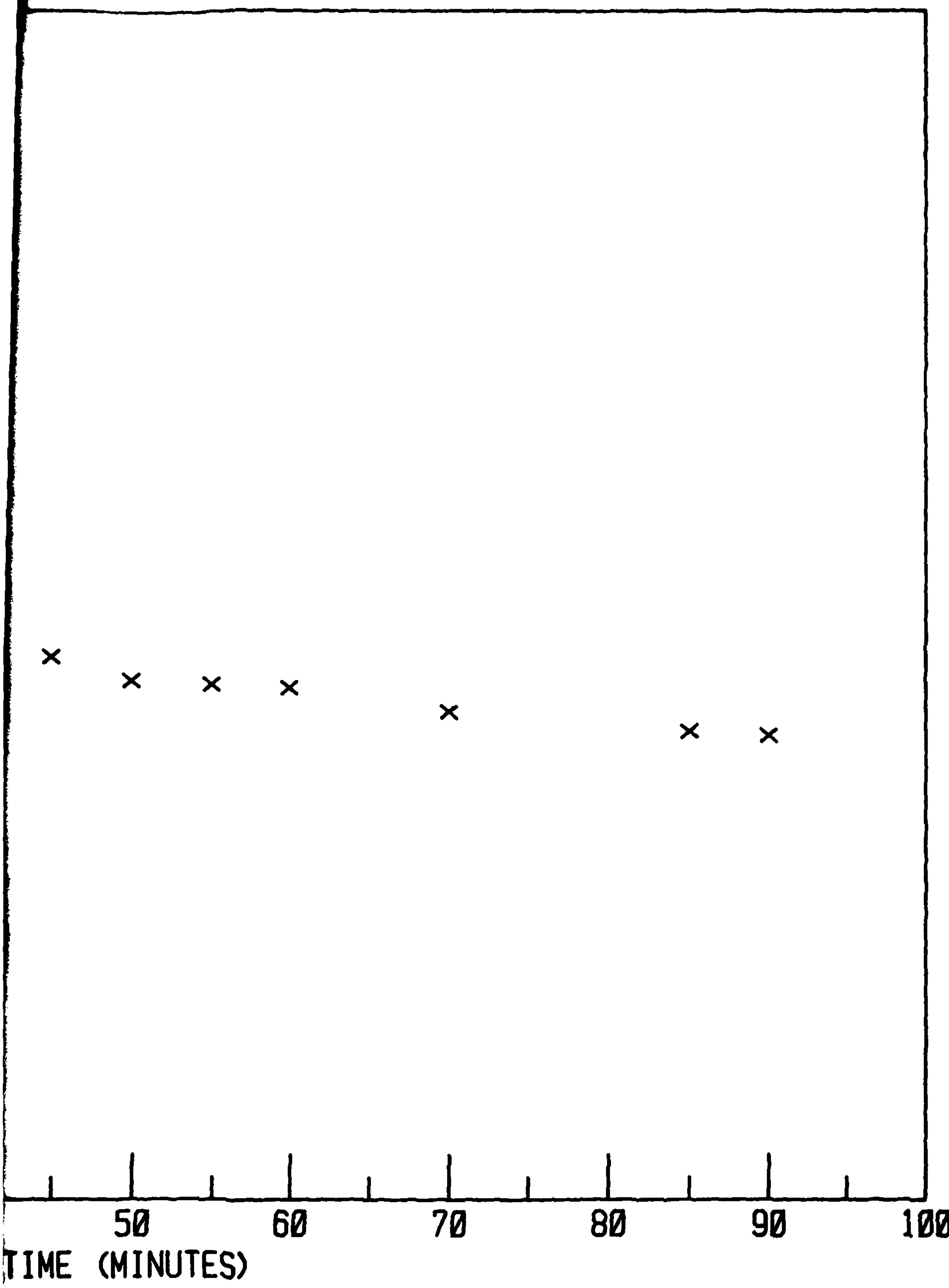
Cycle Rate: 8-10H

Lowest Temperature: 249k

2



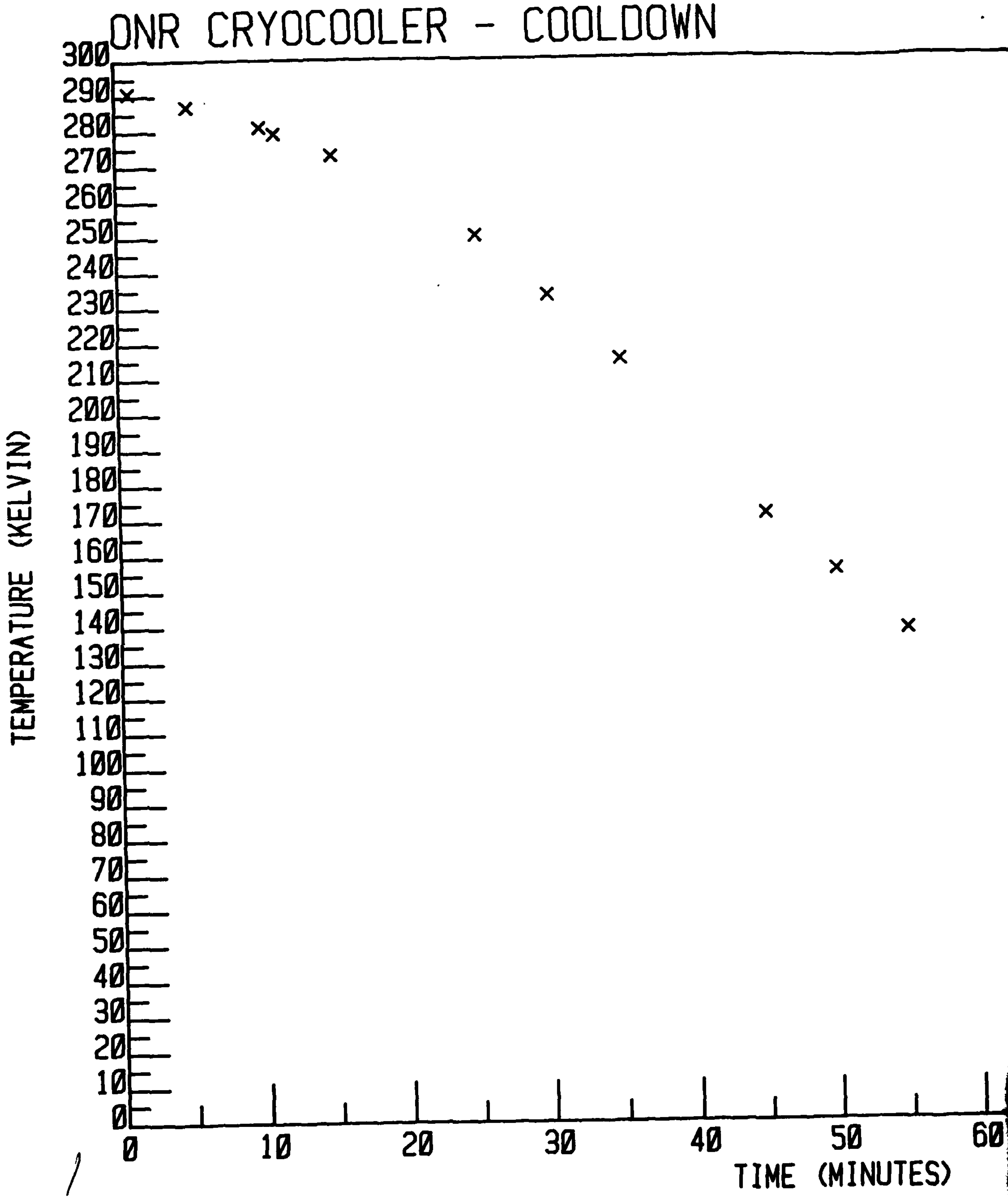
ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
TIME (MINUTES)

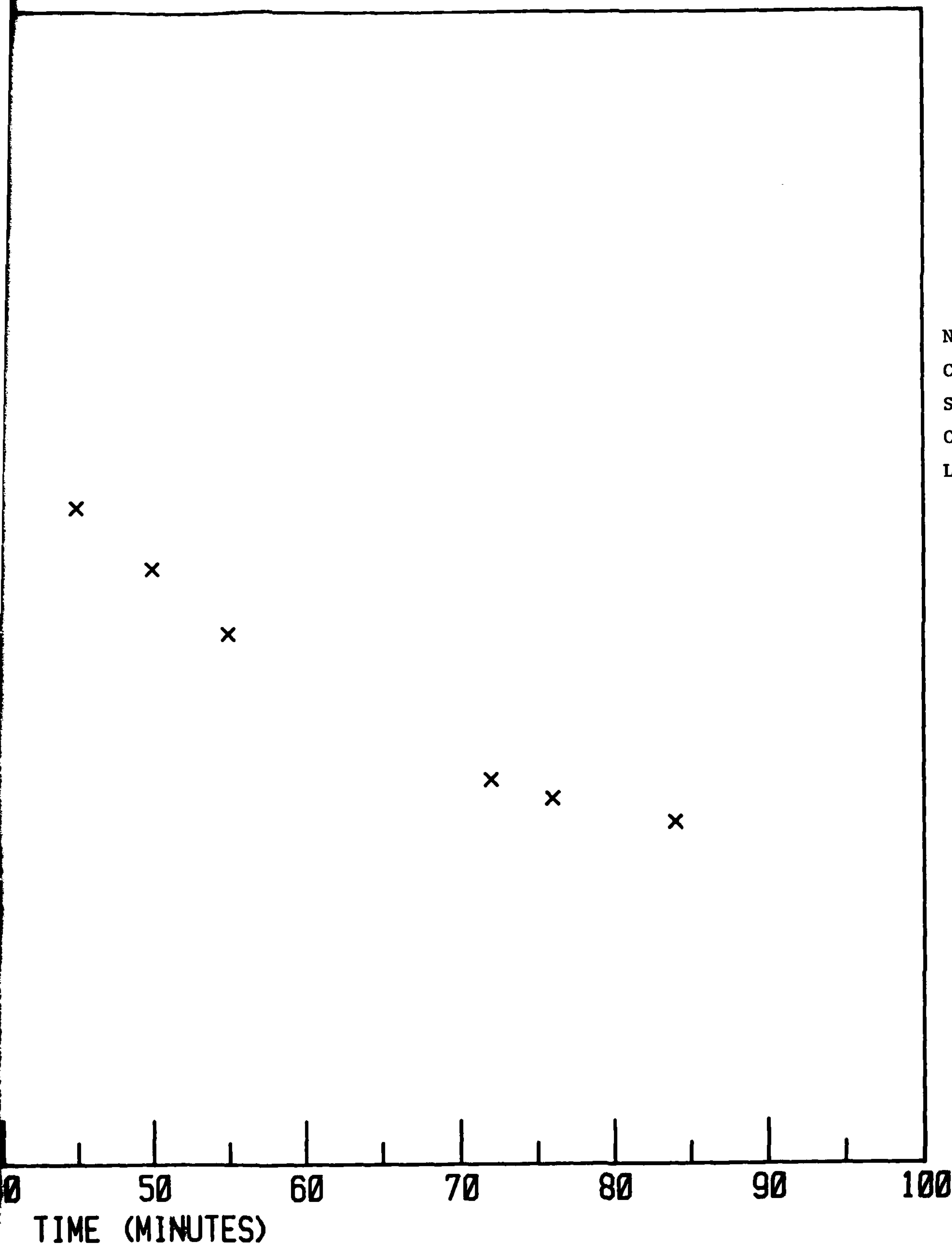


PLOT NO. 7

No. of Stages:	2
Charge Pressure:	1MPa
Stroke Control:	yes
Cycle Rate:	3-6Hz
Lowest Temperature:	117k

2

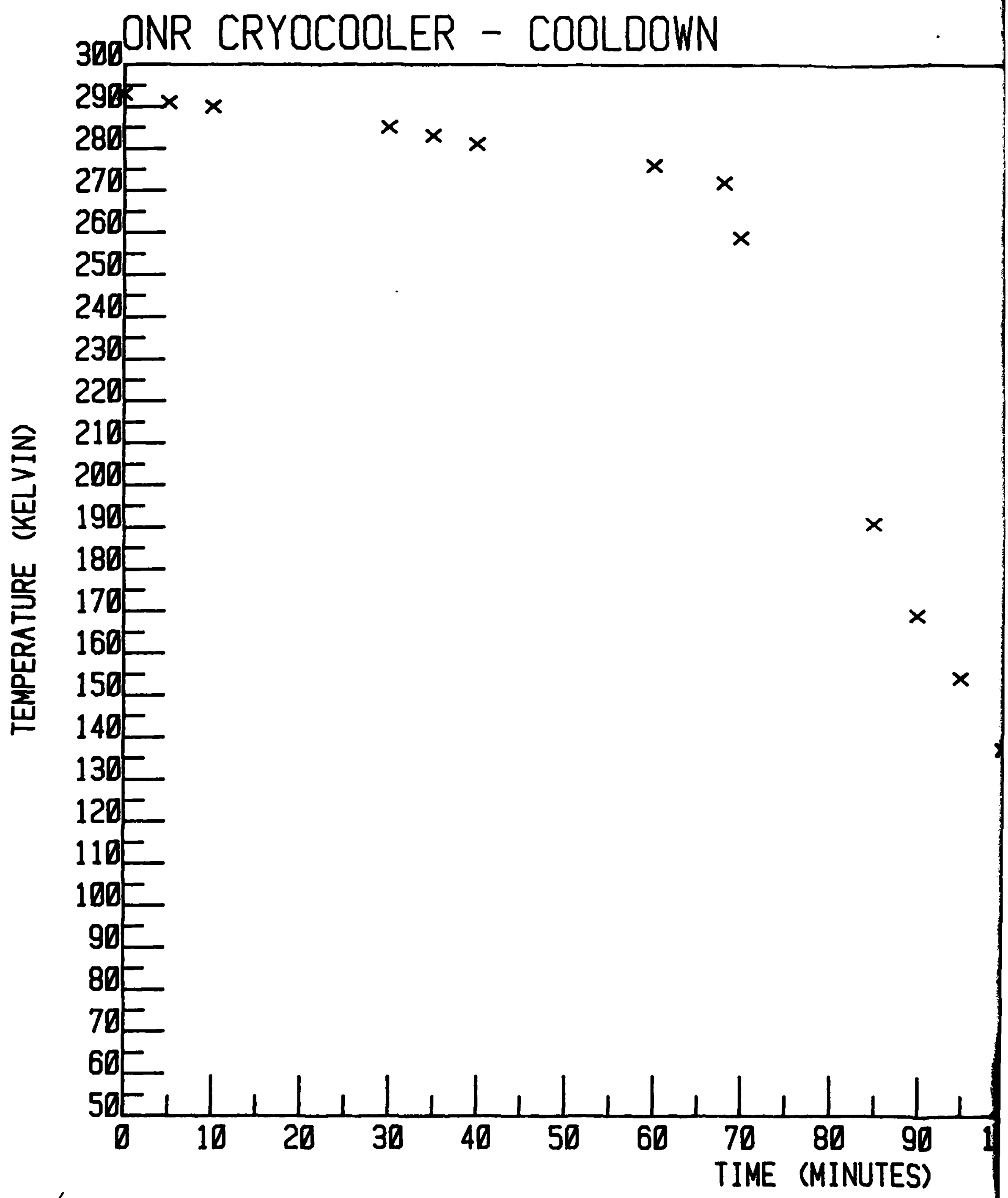

ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
TIME (MINUTES)



PLOT NO. 8

No. of Stages:	2
Charge Pressure:	1.4
Stroke Control:	yes
Cycle Rate:	6Hz
Lowest Temperature:	89k

2


ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
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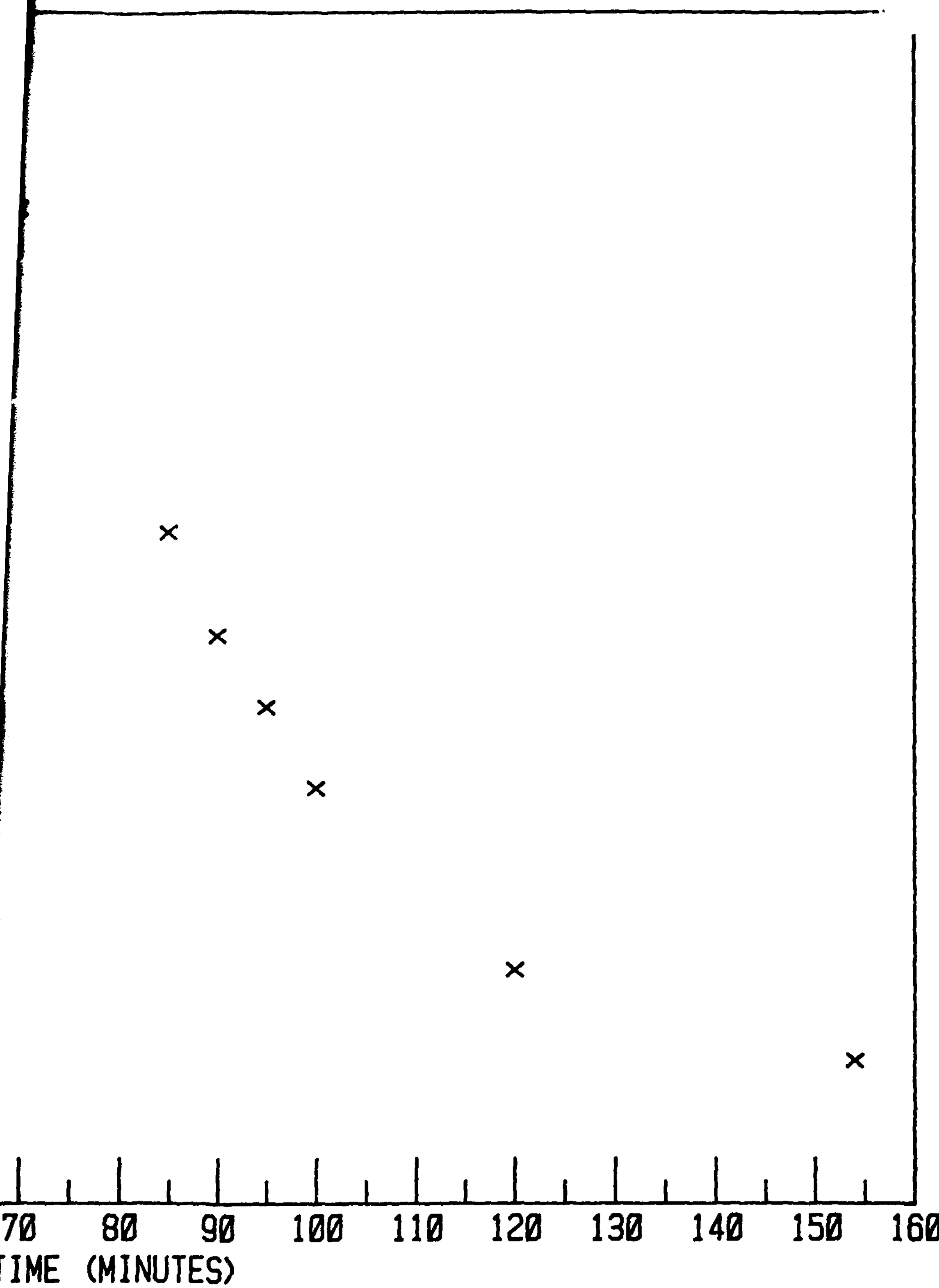
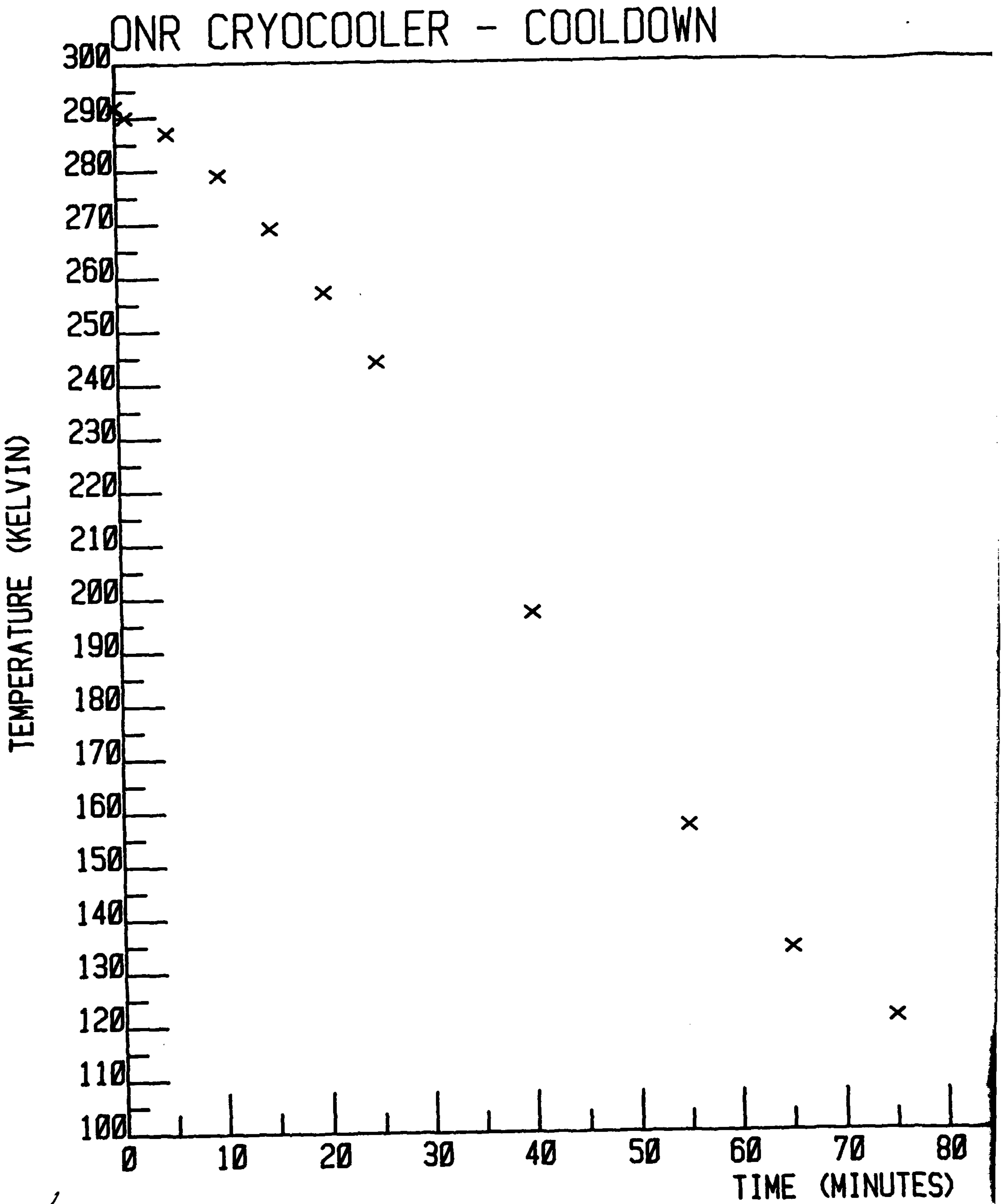
50
0
10
20
30
40
50
60
70
80
90
TIME (MINUTES)

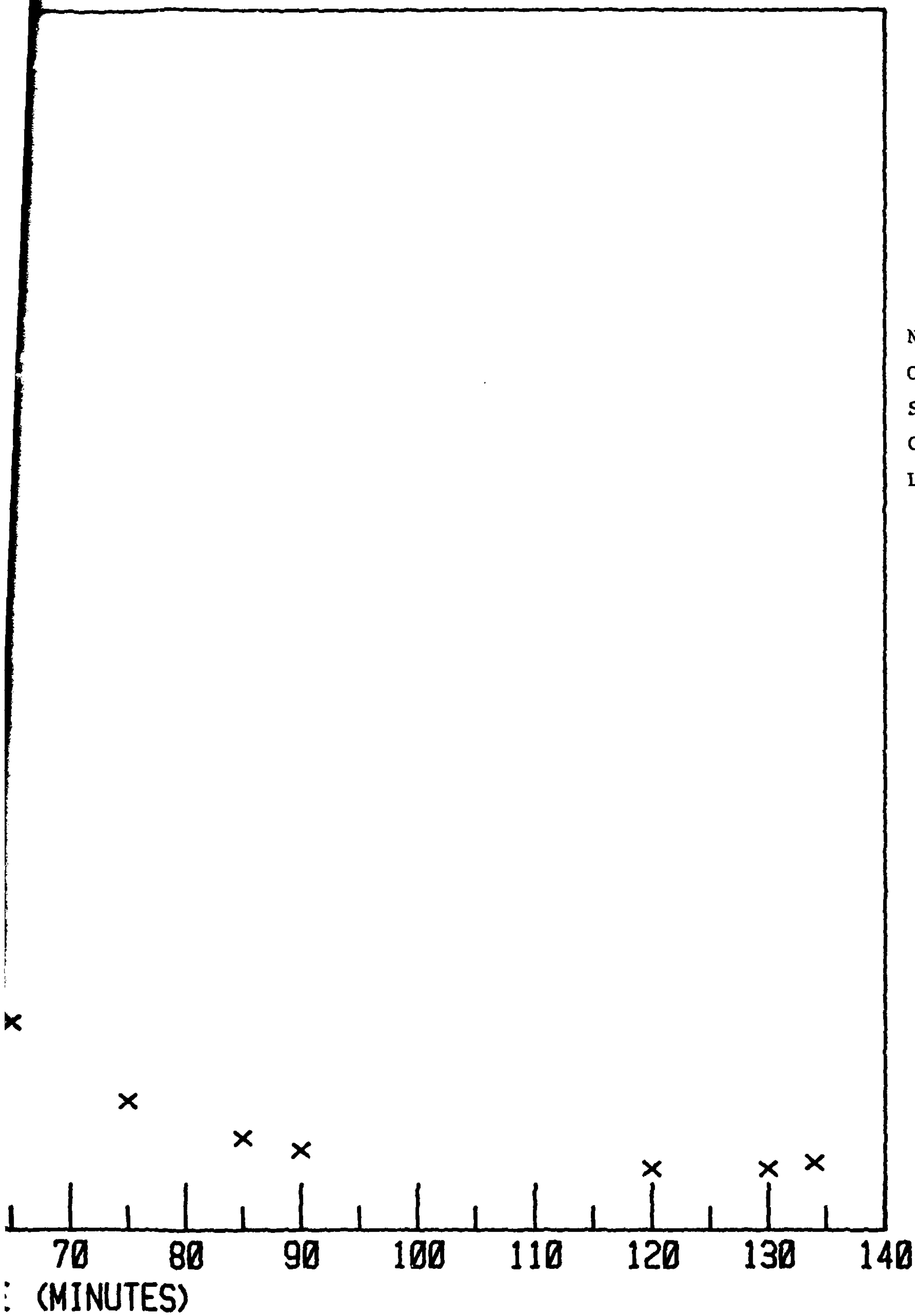


PLOT NO. 9

No. of Stages:	2
Charge Pressure:	.7MPa
Stroke Control:	yes
Cycle Rate:	2-3Hz
Lowest Temperature:	80k

2

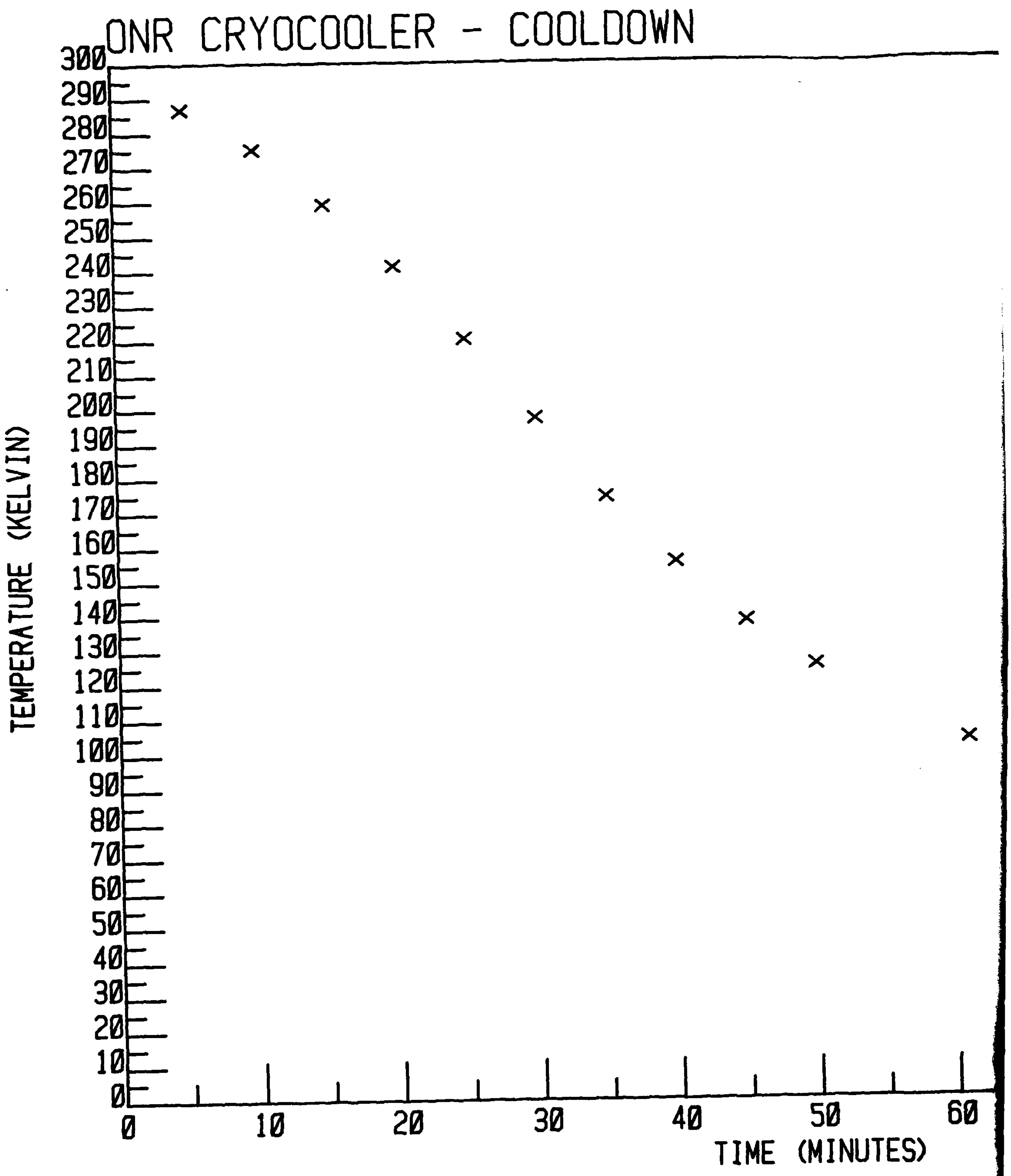

ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
0
10
20
30
40
50
60
70
80
TIME (MINUTES)

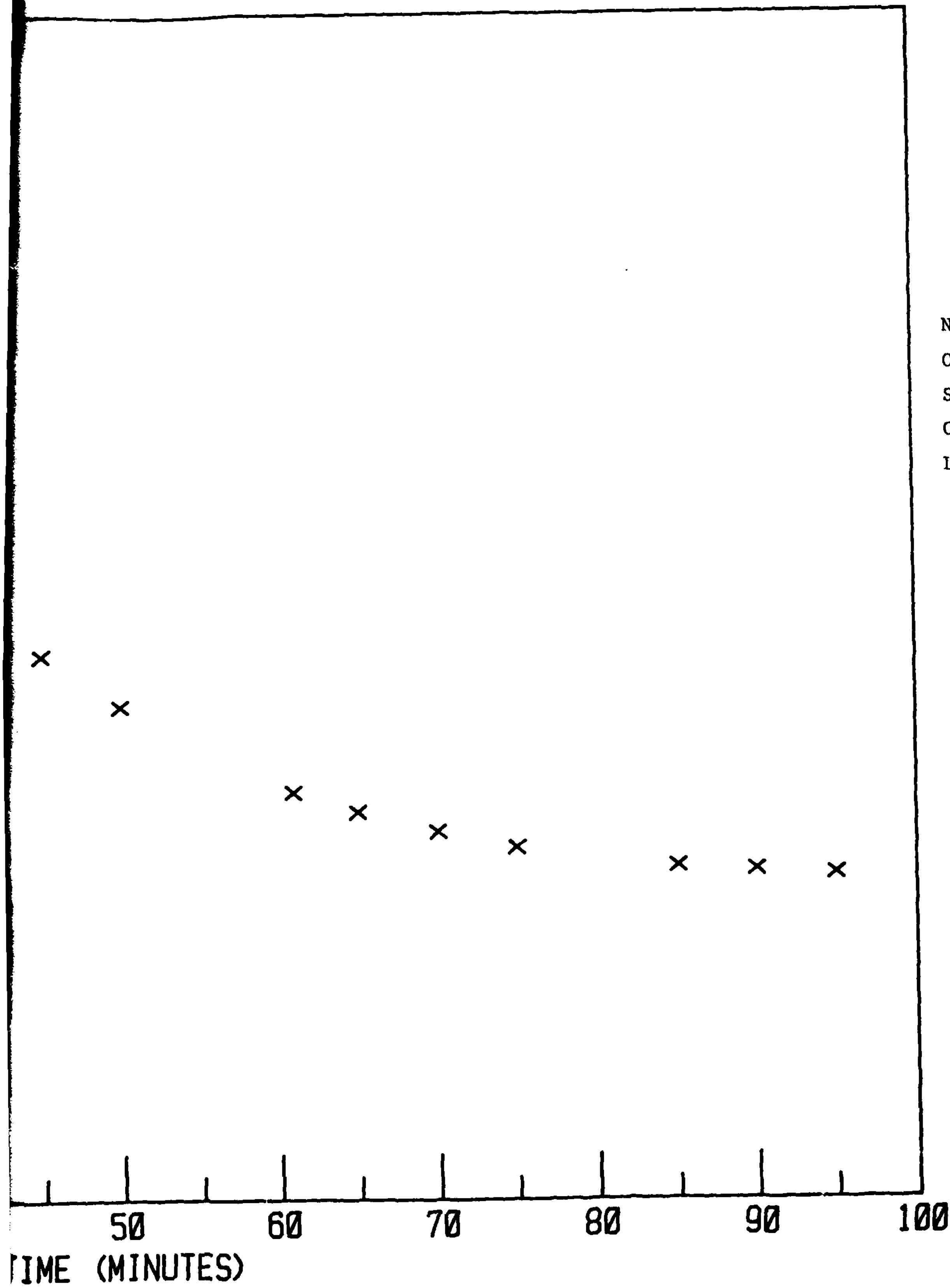


PLOT NO. 10

No. of Stages:	2
Charge Pressure:	1MPa
Stroke Control:	yes
Cycle Rate:	3-5Hz
Lowest Temperature:	110k

2

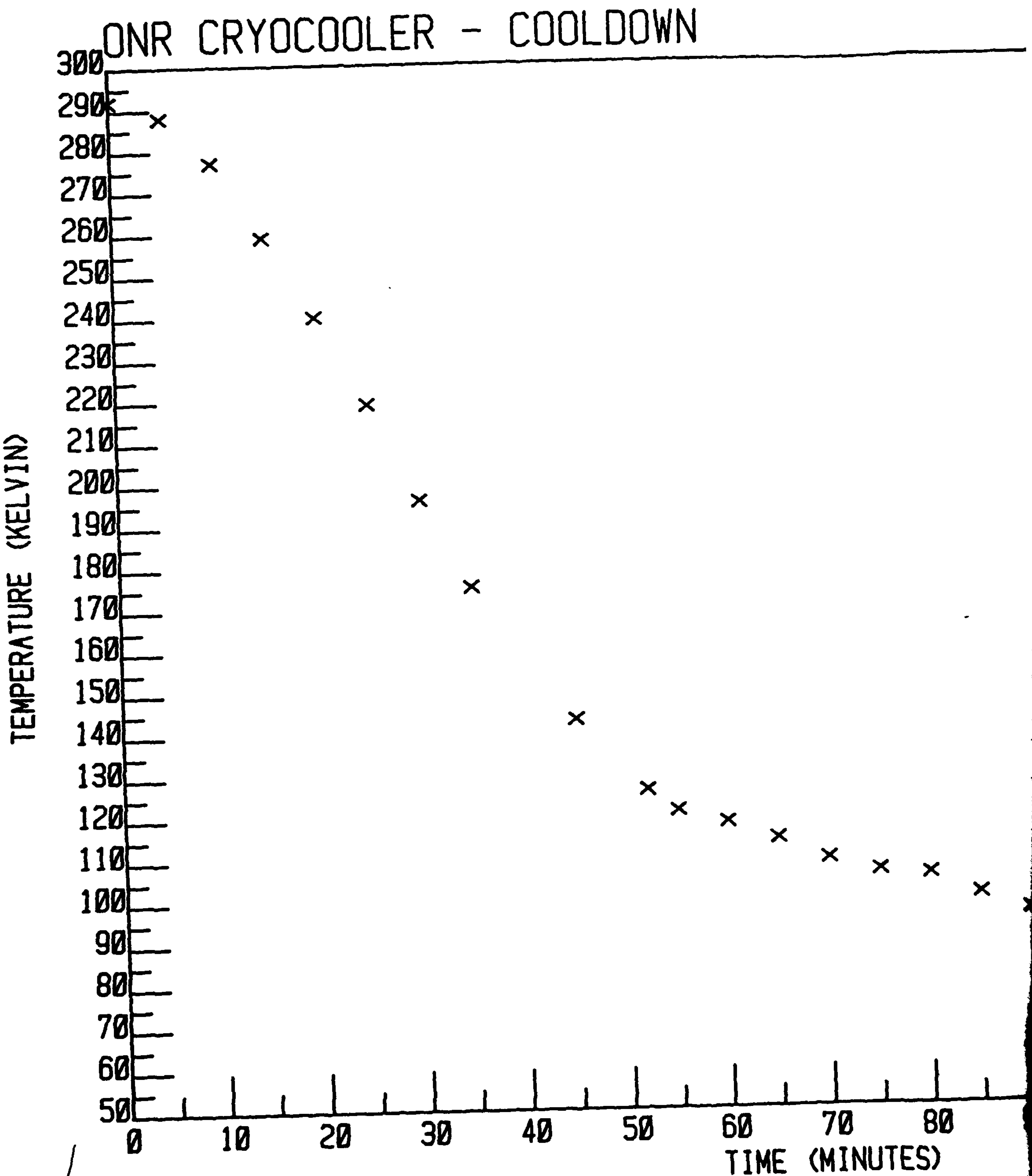

ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
TIME (MINUTES)

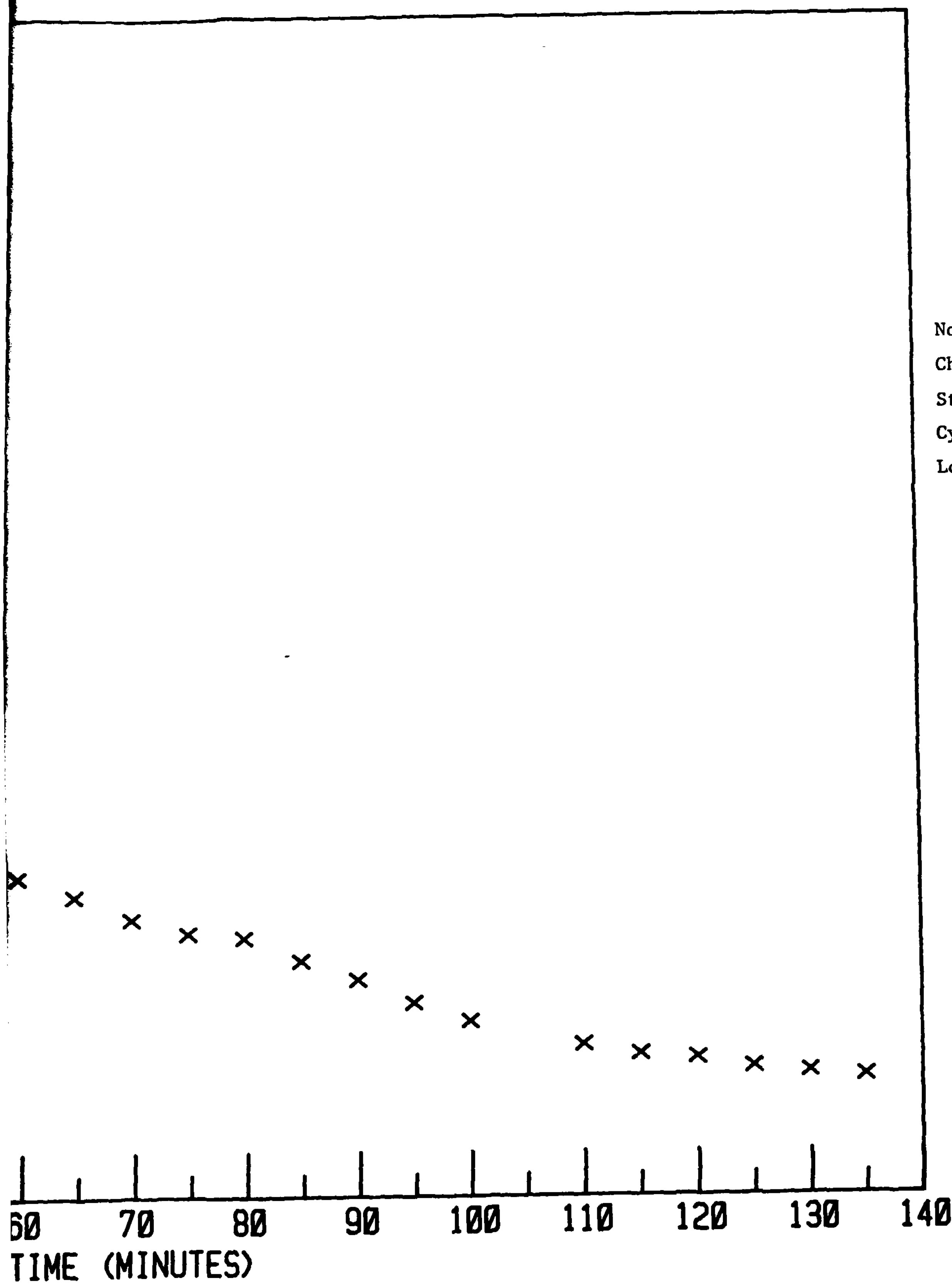


PLOT NO. 11

No. of Stages:	4
Charge Pressure	1.4MPa
Stroke Control:	yes
Cycle Rate:	3-8Hz
Lowest Temperature:	82k

2

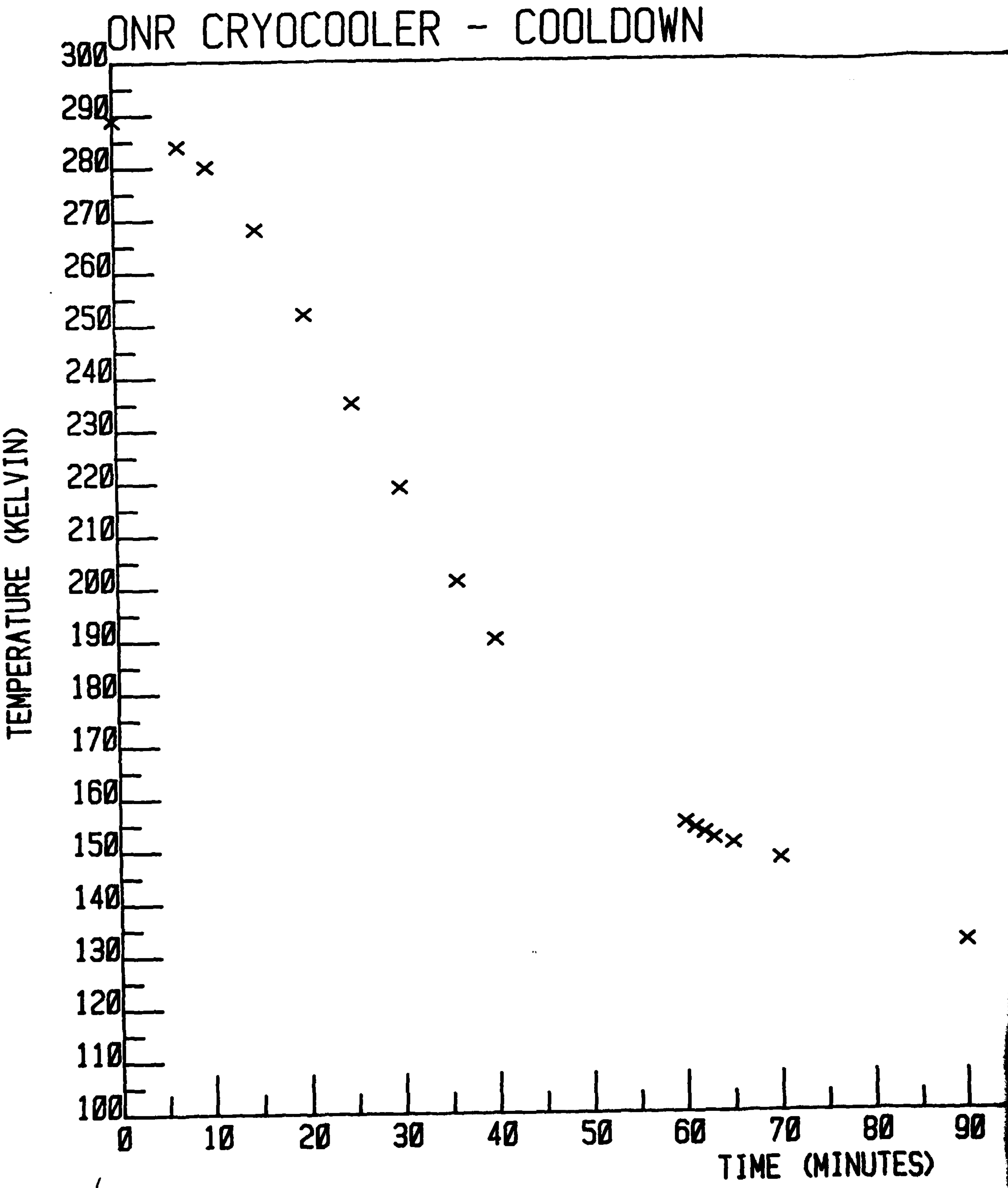

ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
0
10
20
30
40
50
60
70
80
TIME (MINUTES)

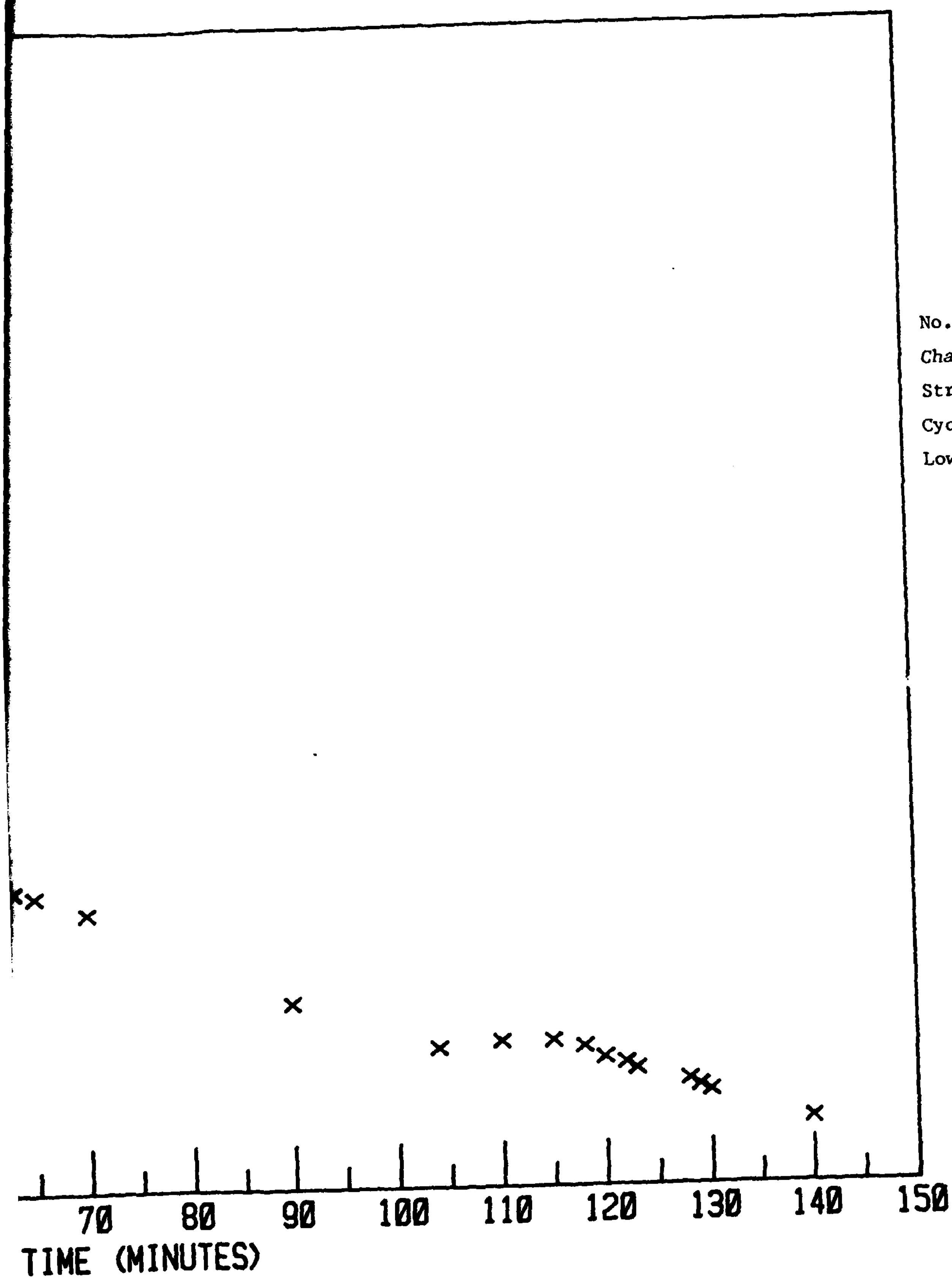


PLOT NO. 12

No. of Stages:	4
Charge Pressure:	1.4MPa
Stroke Control:	yes
Cycle Rate:	7-10Hz
Lowest Temperature:	75k

2


ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
0
10
20
30
40
50
60
70
80
90
TIME (MINUTES)



PLOT NO. 13

No. of Stages: 2

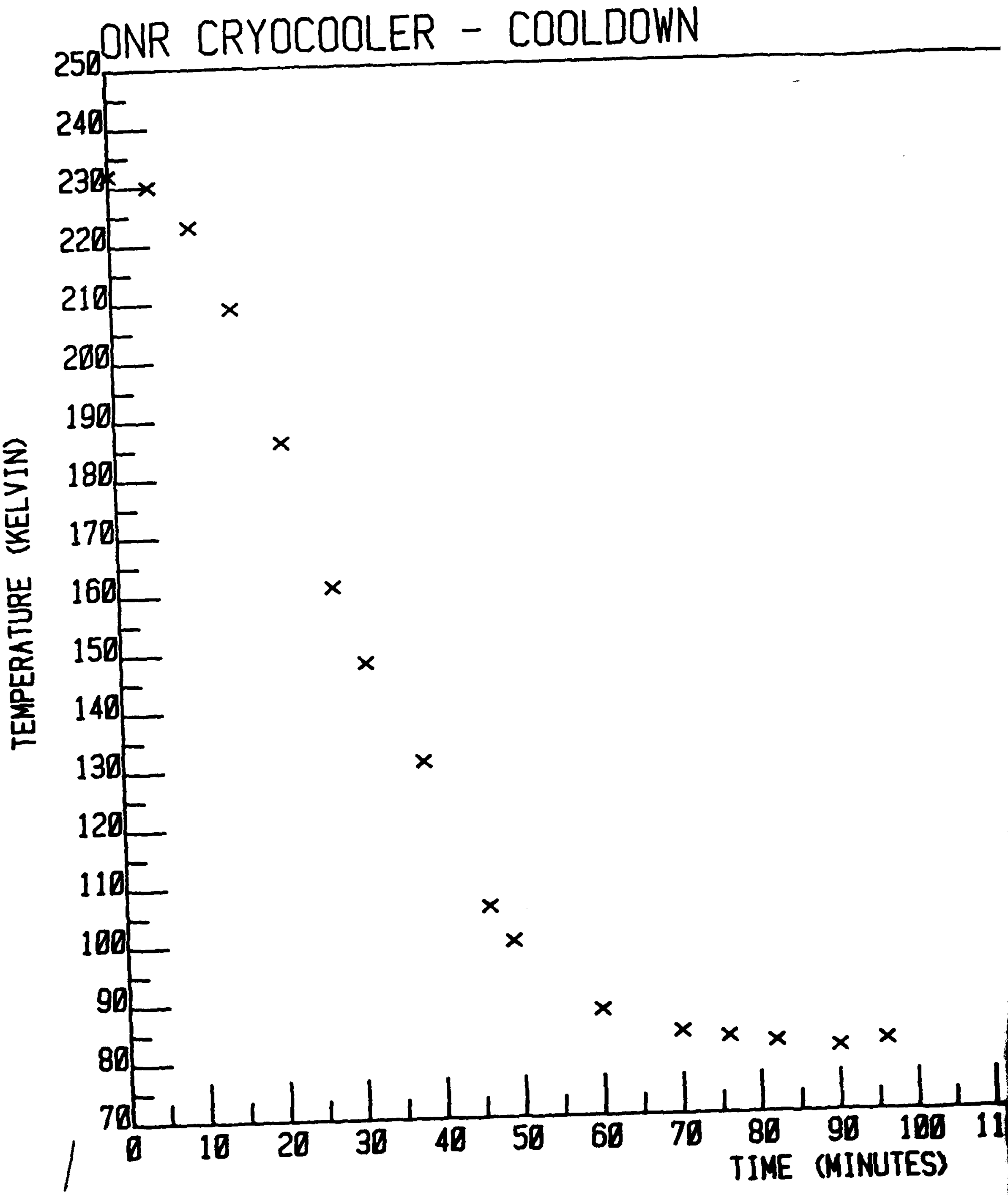
Charge Pressure: 1.4MPa

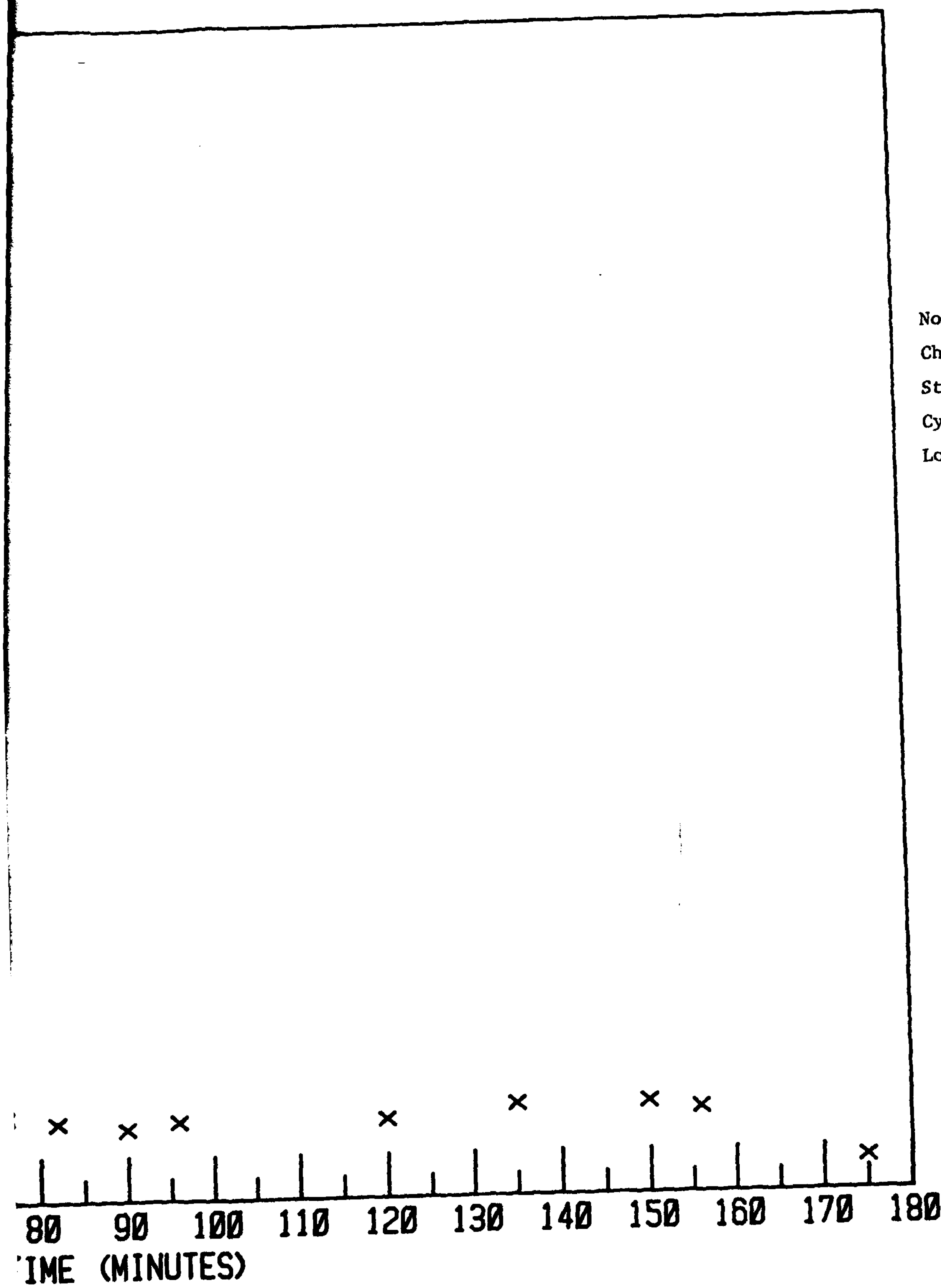
Stroke Control: yes

Cycle Rate: 4-8Hz

Lowest Temperature: 111k

2

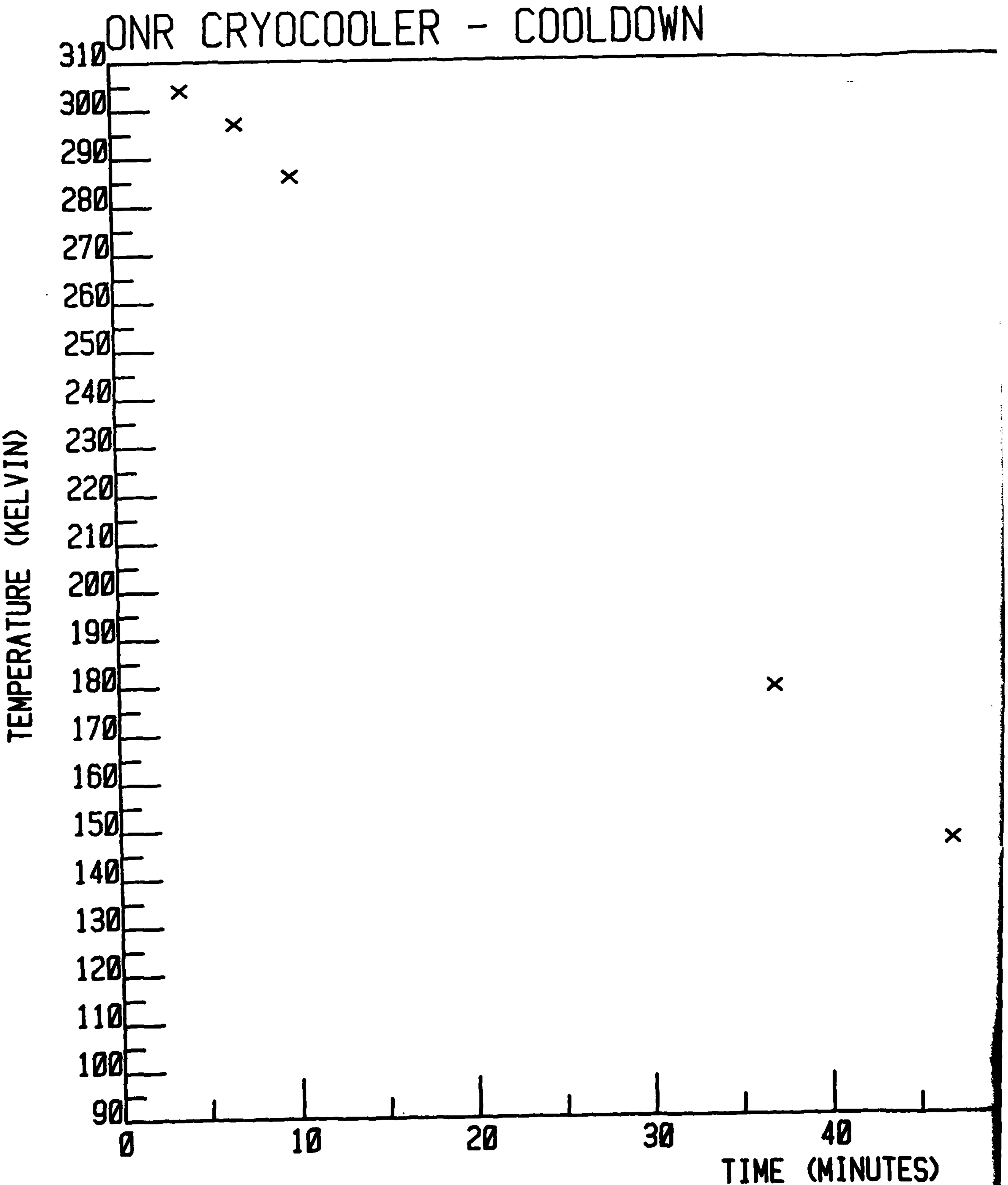

ONR CRYOCOOLER - COOLDOWN
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
TEMPERATURE (KELVIN)
0
10
20
30
40
50
60
70
80
90
100
11
TIME (MINUTES)



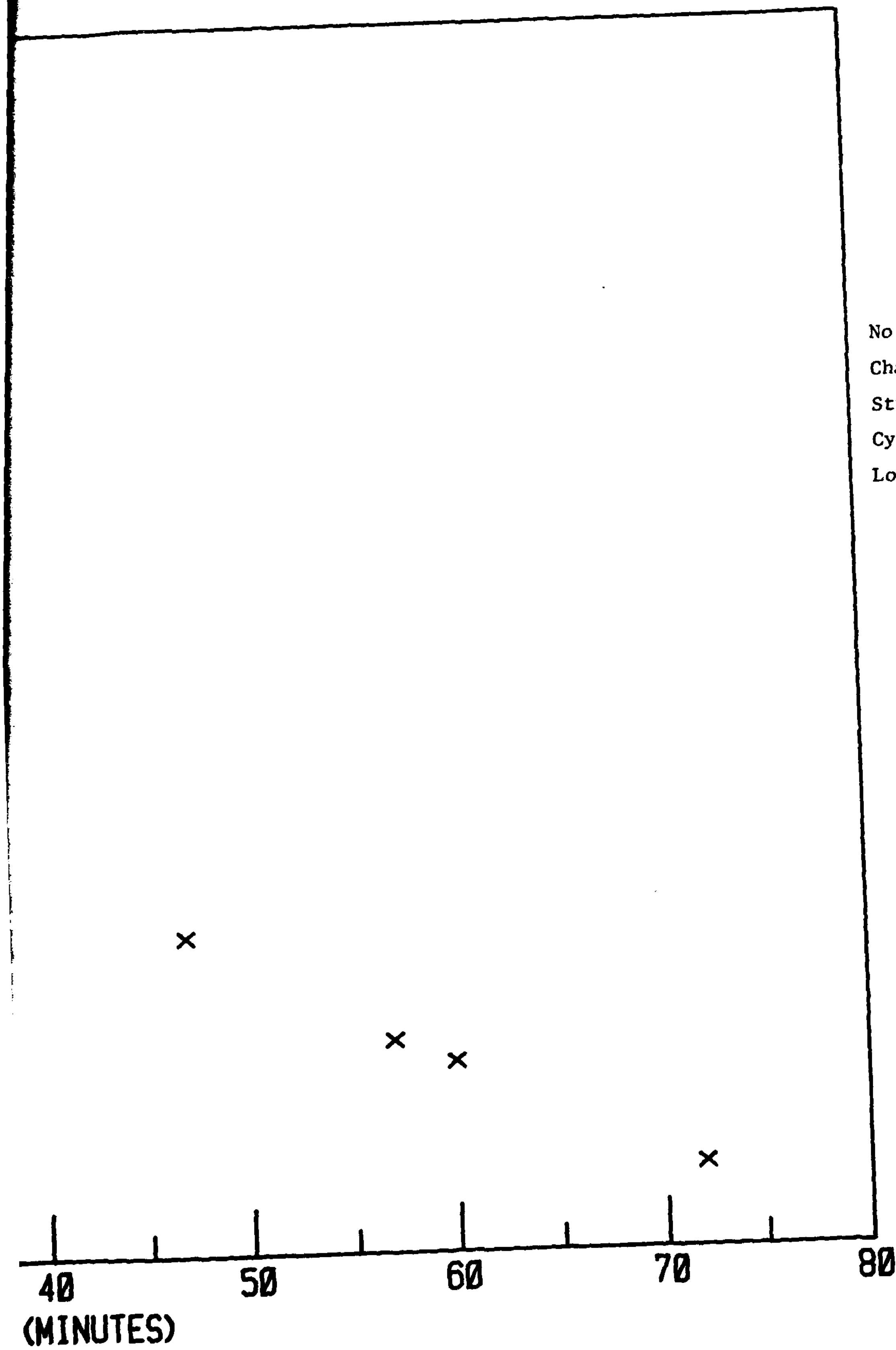
PLOT NO. 14

No. of Stages:	4
Charge Pressure:	1.4MPa
Stroke Control:	yes
Cycle Rate:	3-6Hz
Lowest Temperature:	75k

2



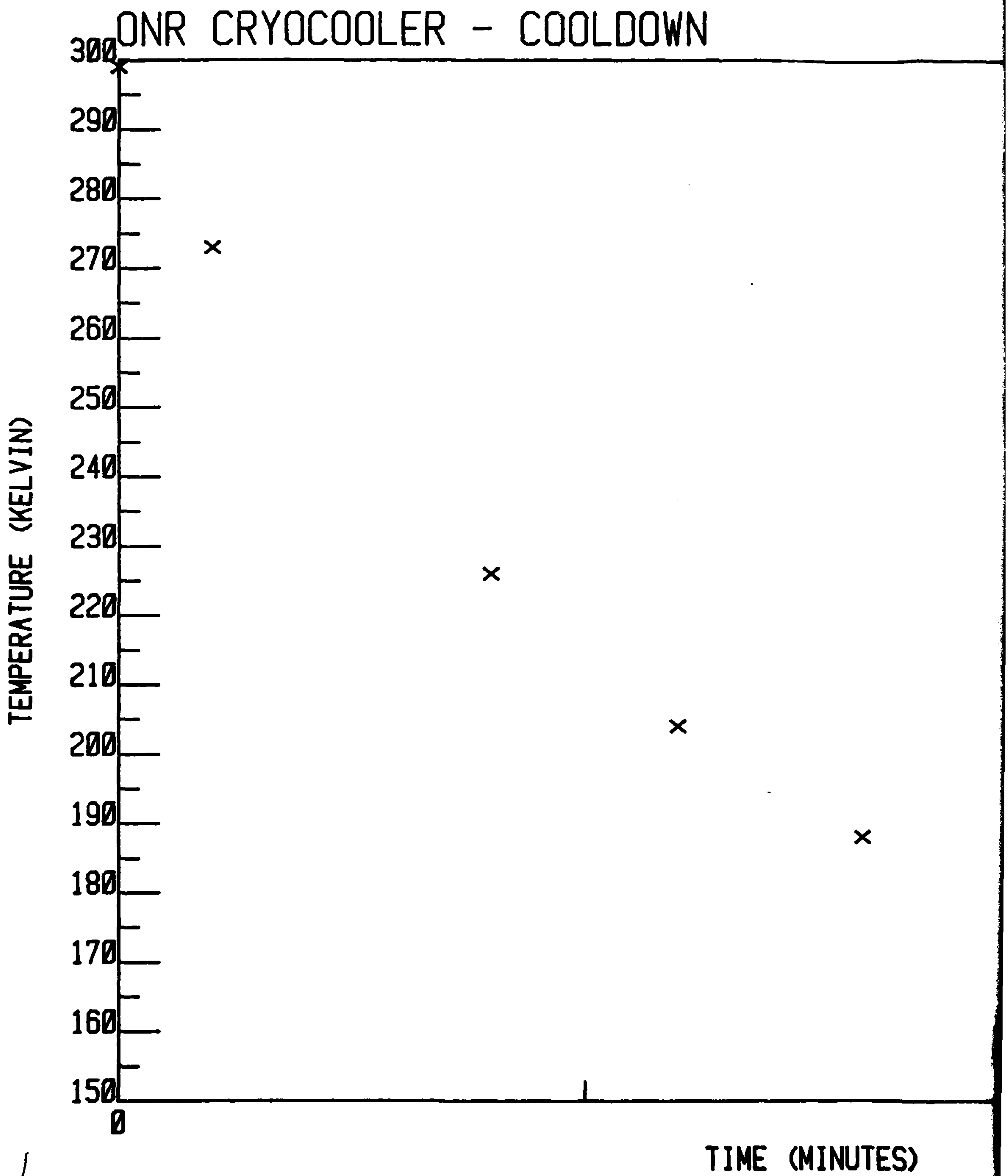
ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
310
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
0
10
20
30
40
TIME (MINUTES)

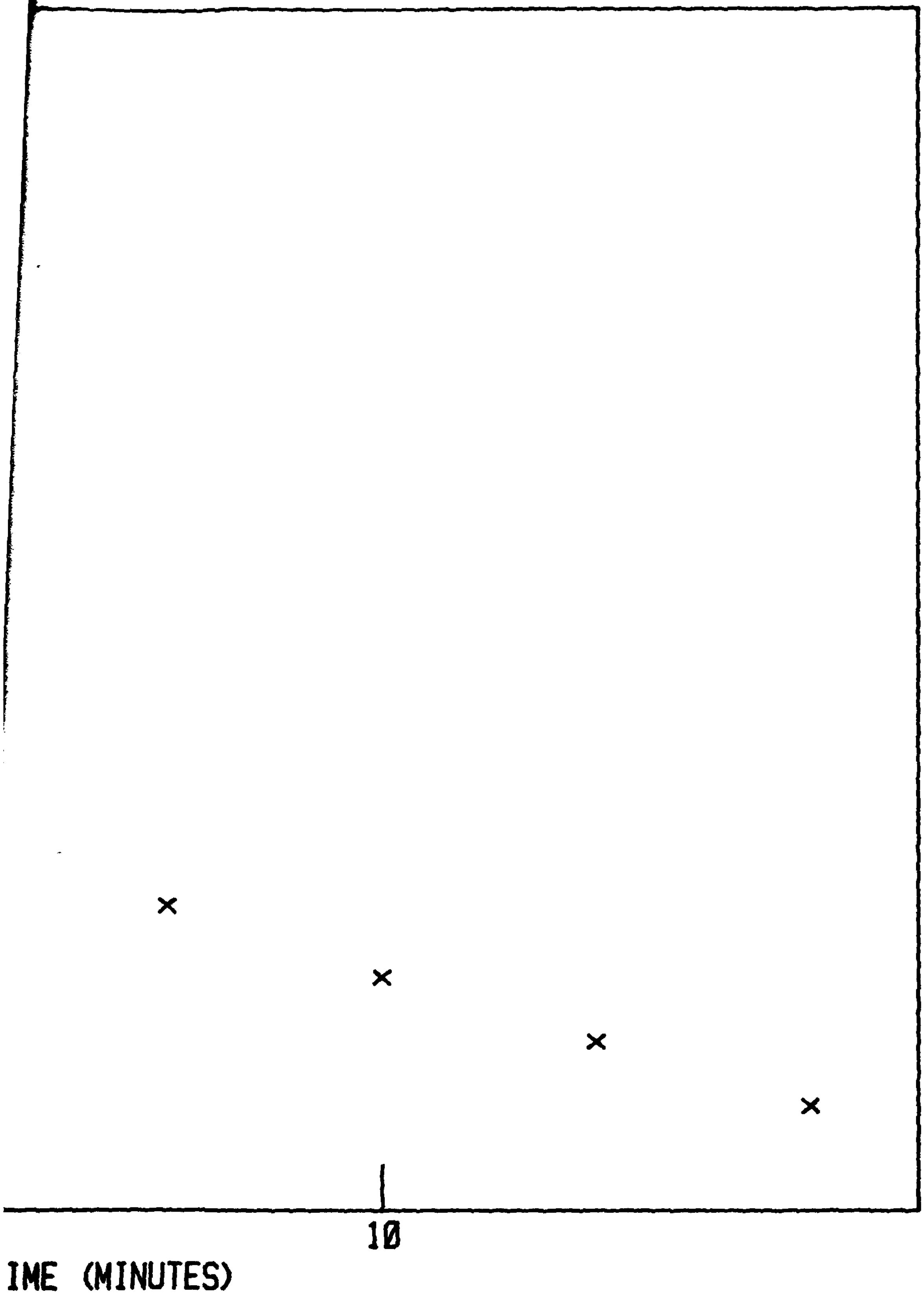


PLOT NO. 15

No. of Stages: 2
Charge Pressure: 1.4MPa
Stroke Control: yes
Cycle Rate: not measured
Lowest Temperature: 105k

2

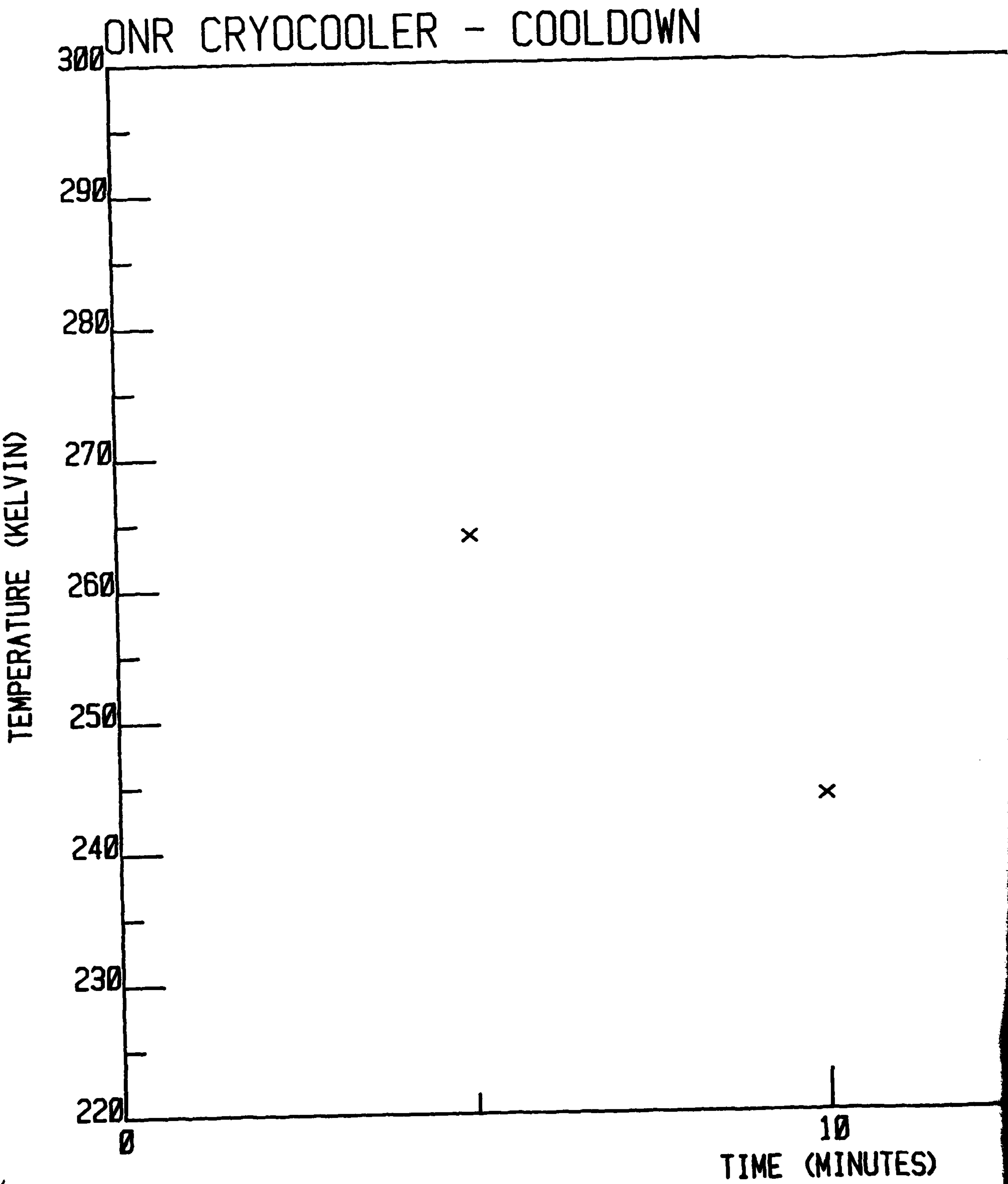

ONR CRYOCOOLER - COOLDOWN
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
0
TEMPERATURE (KELVIN)
TIME (MINUTES)

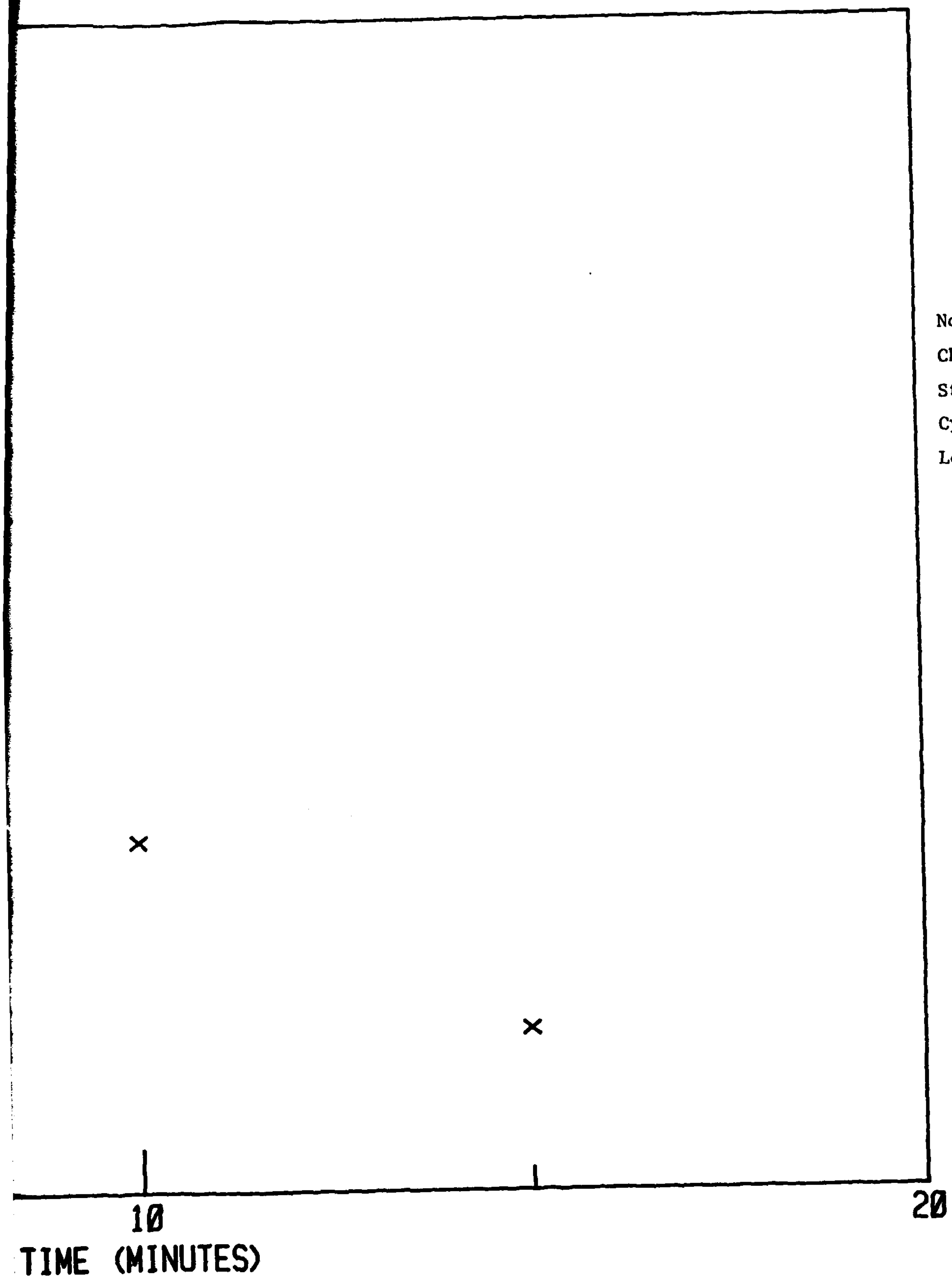


PLOT NO. 16

No. of Stages:	2
Charge Pressure:	1MPa
Stroke Control:	yes
Cycle Rate:	4Hz
Lowest Temperature:	163k

2

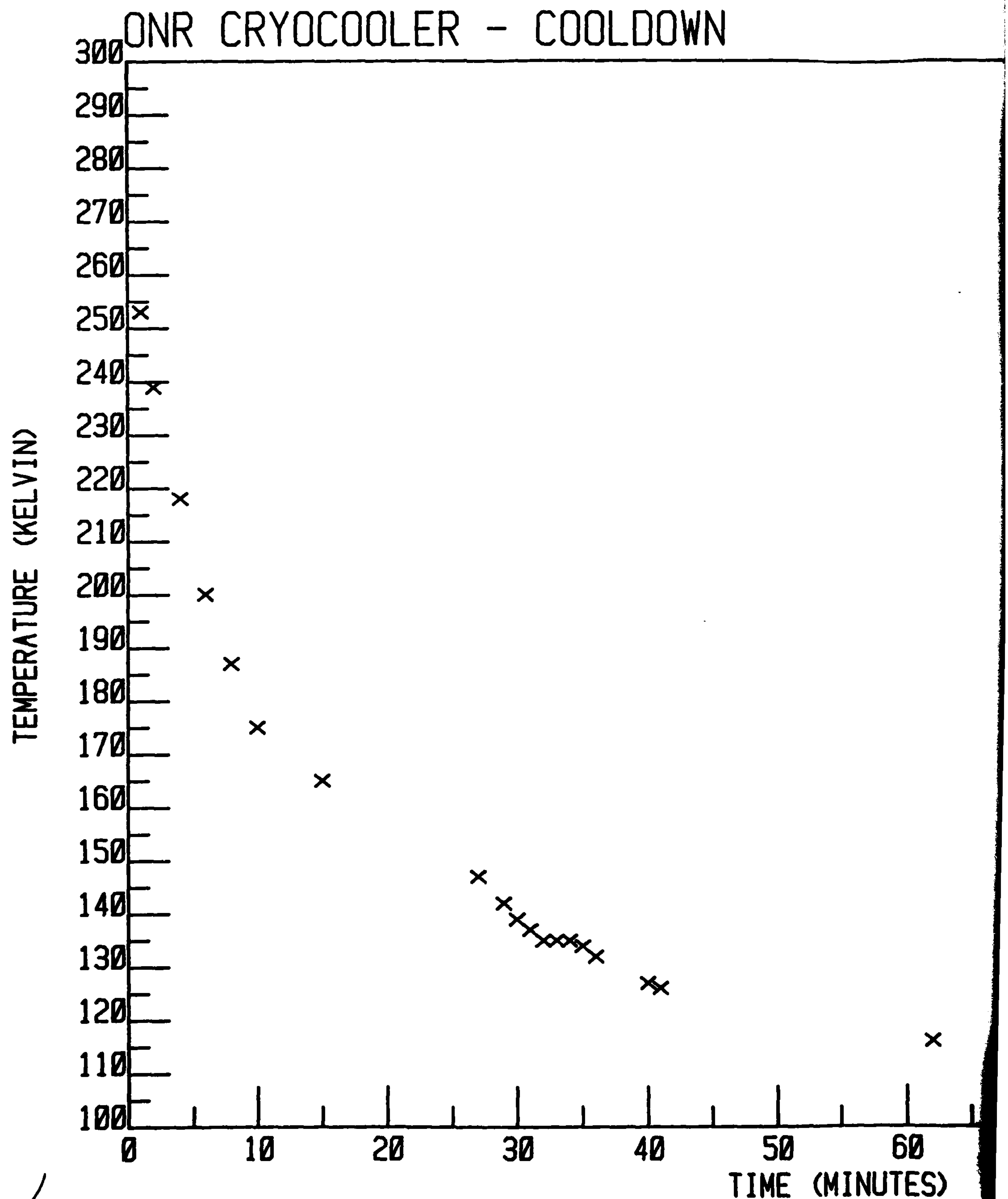

ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
0
10
TIME (MINUTES)

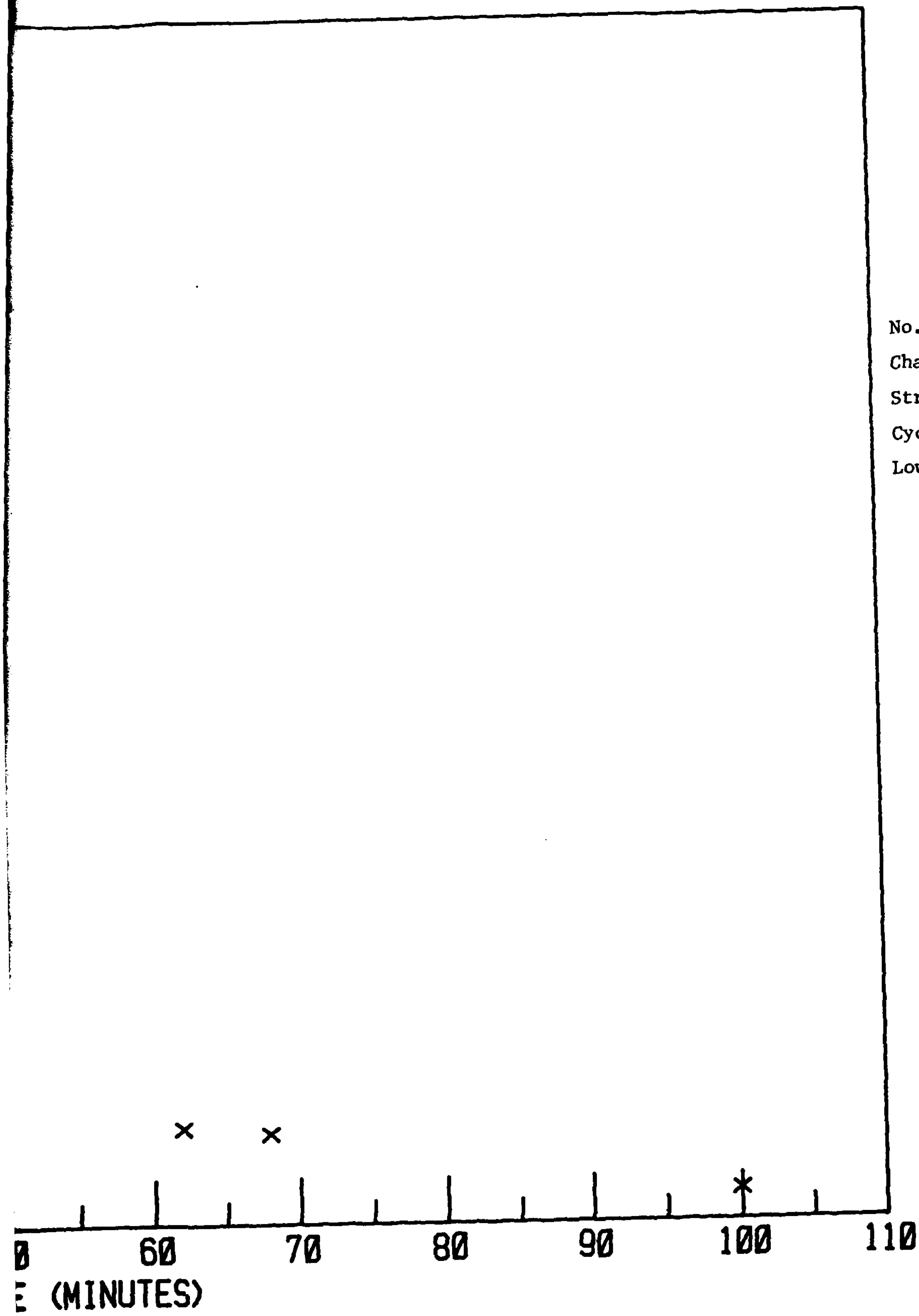


PLOT NO. 17

No. of Stages:	2
Charge Pressure:	1.4MPa
Stroke Control:	yes
Cycle Rate:	6-8Hz
Lowest Temperature:	231k

2


ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
0
10
20
30
40
50
60
TIME (MINUTES)



PLOT NO. 18

No. of Stages: 2

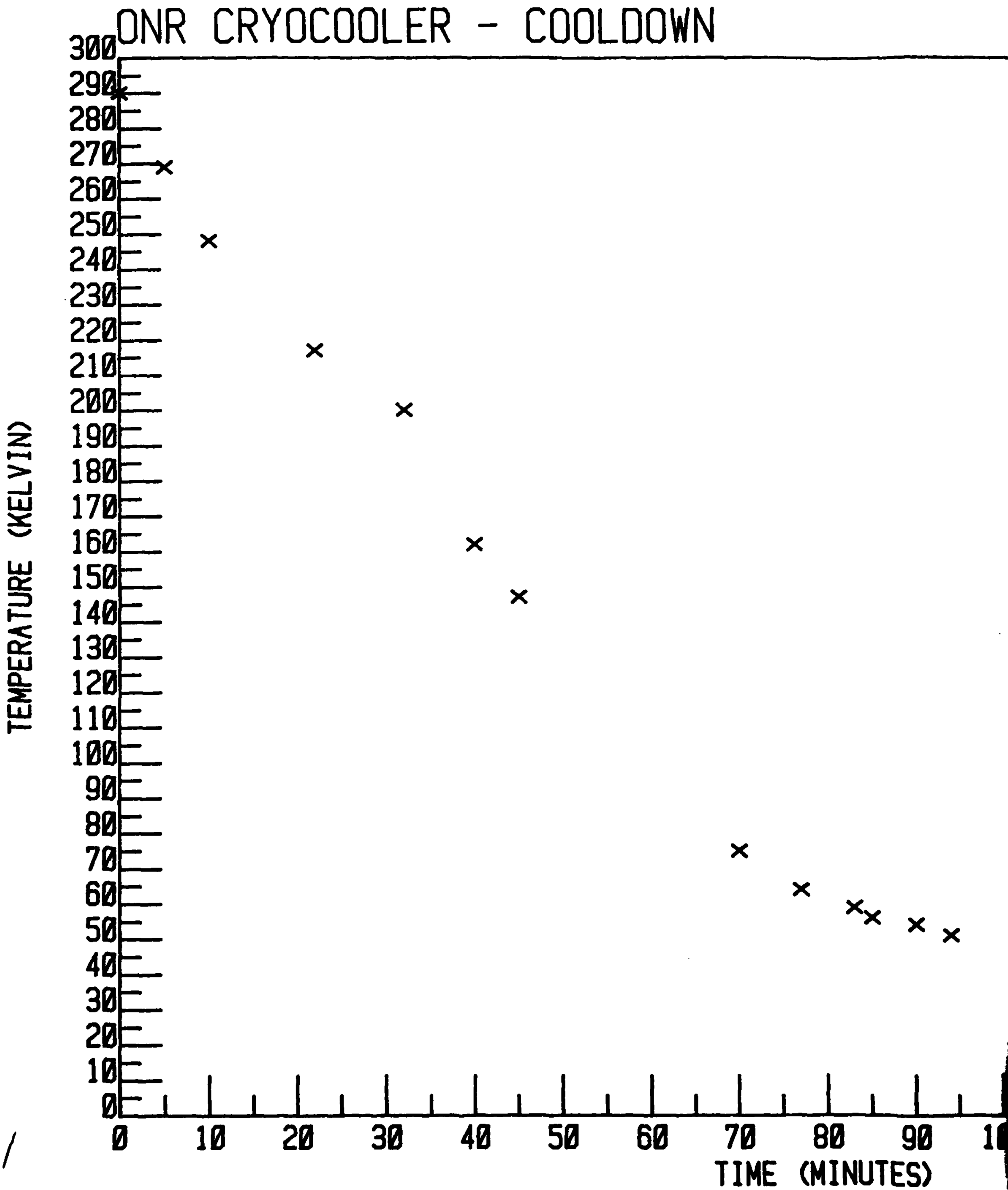
Charge Pressure: 1MPa

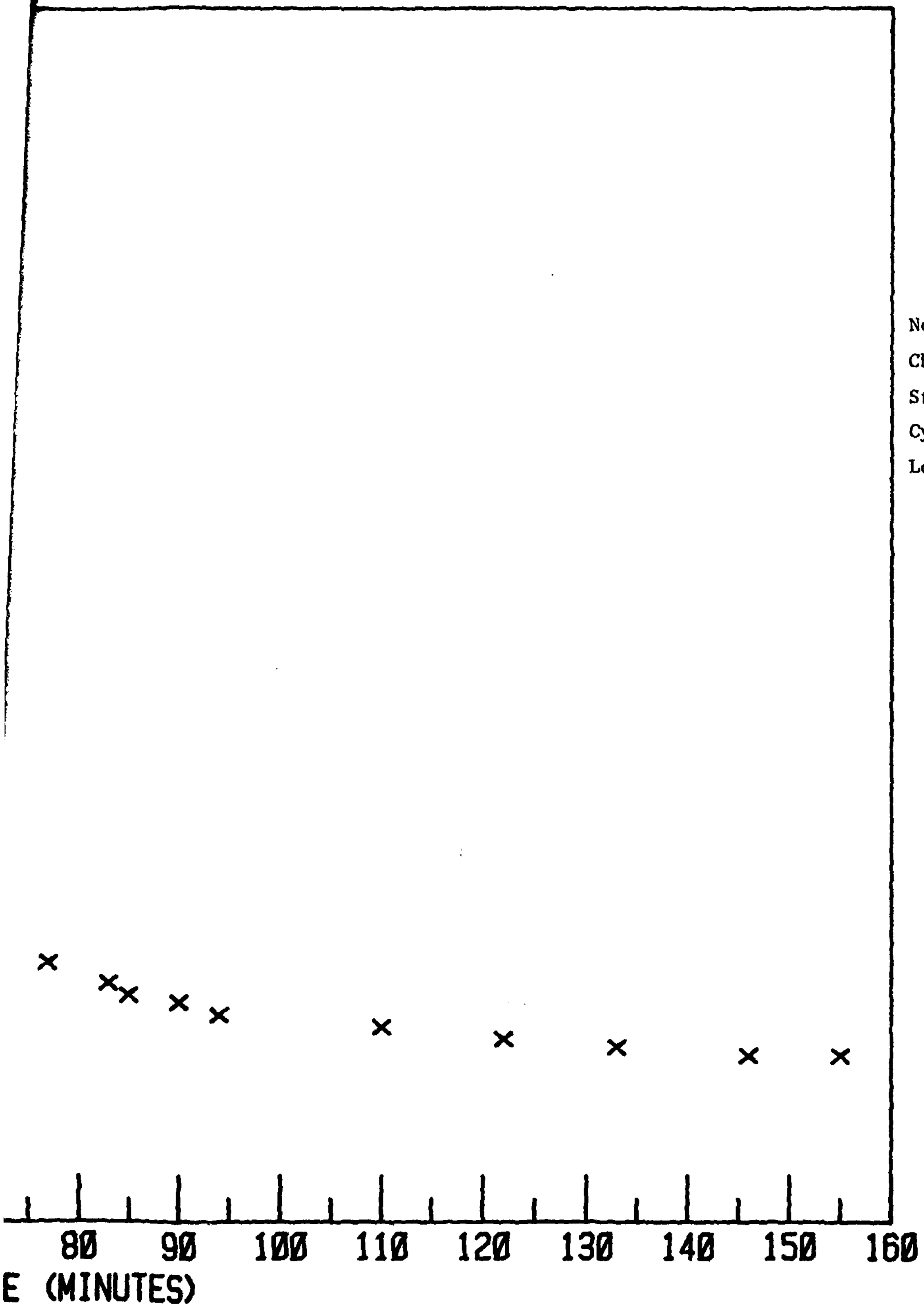
Stroke Control: yes

Cycle Rate: 2-6Hz

Lowest Temperature: 105k

2


ONR CRYOCOOLER - COOLDOWN
TEMPERATURE (KELVIN)
TIME (MINUTES)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300



PLOT NO. 19

No. of Stages: 2
Charge Pressure: .6MPa
Stroke Control: yes
Cycle Rate: 2.5~4Hz
Lowest Temperature: 41k

2